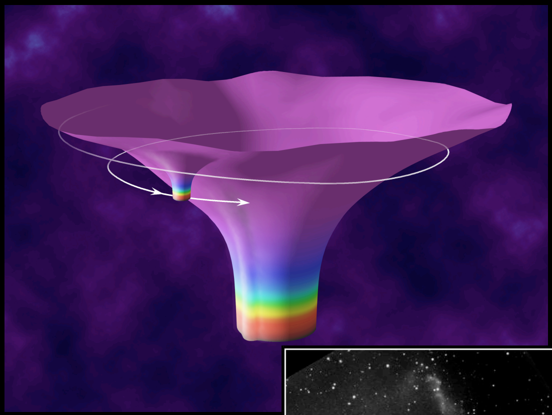
'astrophysics tutorial'

A quick walk through LISA sources

What gravitational waves are uniquely suited to teach us about these systems.



Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2
PRC97-34a • ST ScI OPO • October 21, 1997 • B. Whitmore (ST ScI) and NASA

The electromagnetic universe: Dynamics of charges and plasmas

Leading order effect is time variation of charge dipole moment:

$$d_a = \int \rho_q(x')x'_a \, d^3x'$$

$$A_a \simeq \frac{\dot{d}_a}{r} \sim \frac{qv}{r}$$

Strong coupling! Coefficient of radiation field is 1 in "correct" units.

Strong coupling means radiation is readily created, (relatively) easily measured.

The gravitational wave universe: Things that are dense and relativistic

At leading order, GR teaches us that GWs are generated by the time variation of a source's "mass" quadrupole moment.

$$Q_{ab} = \int \rho_m(x') x'_a x'_b \, d^3x'$$

$$h_{ab} \simeq \frac{G}{c^4} \frac{\ddot{Q}_{ab}}{r} \simeq \frac{G}{c^4} \frac{mv^2}{r}$$

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Need large *m* and large *v* to compensate for smallness of G/c^4!

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Need large *m* and large *v* to compensate for smallness of G/c^4 !

Direct probe of spacetime dynamics

Organization of sources

Convenient way to categorize sources:
By search technique. Each broad category presents a different data analysis challenge, requires a very different approach.

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Periodic sources

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Chirping sources

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Stochastic backgrounds

Periodic sources

Chirping sources

Really complicated chirping sources

Cosmological stochastic backgrounds

Concordance model indicates early universe underwent rapid *inflation* driven by a scalar field:

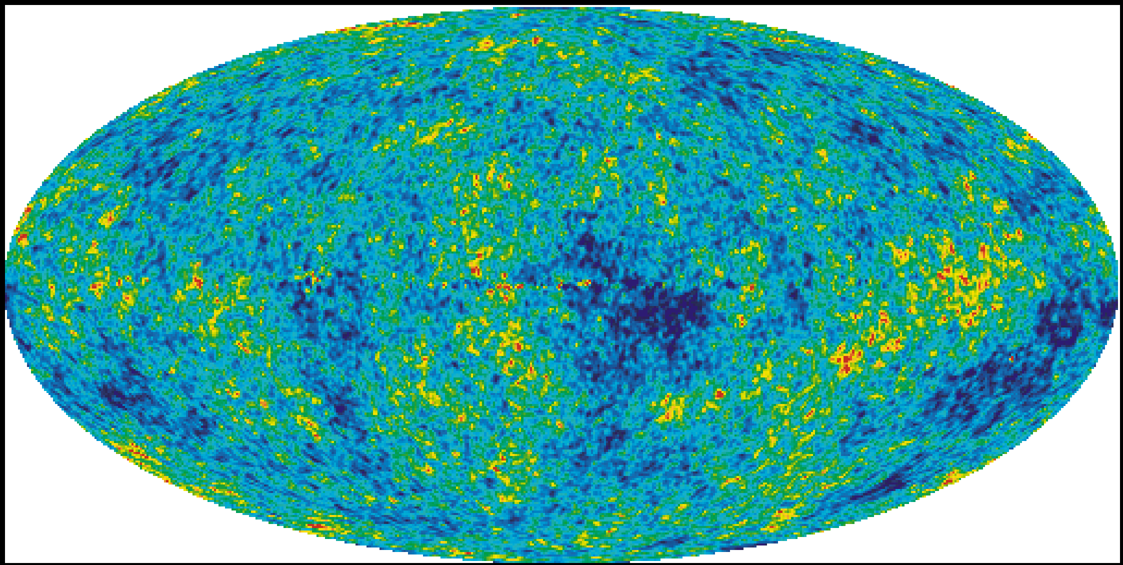
$$\ddot{a} = \frac{8\pi G V(\phi)}{3} a$$

$$\rightarrow \text{Exponential growth}$$

Zero point fluctuations in that field seeded density inhomogeneities

… gives inhomogeneities in the gravitational potential

… leads to fluctuations in the temperature of the cosmic microwave background.



Stunningly good agreement between model and observations!

Cosmological stochastic backgrounds

Spacetime metric also experiences zero-point fluctuations!

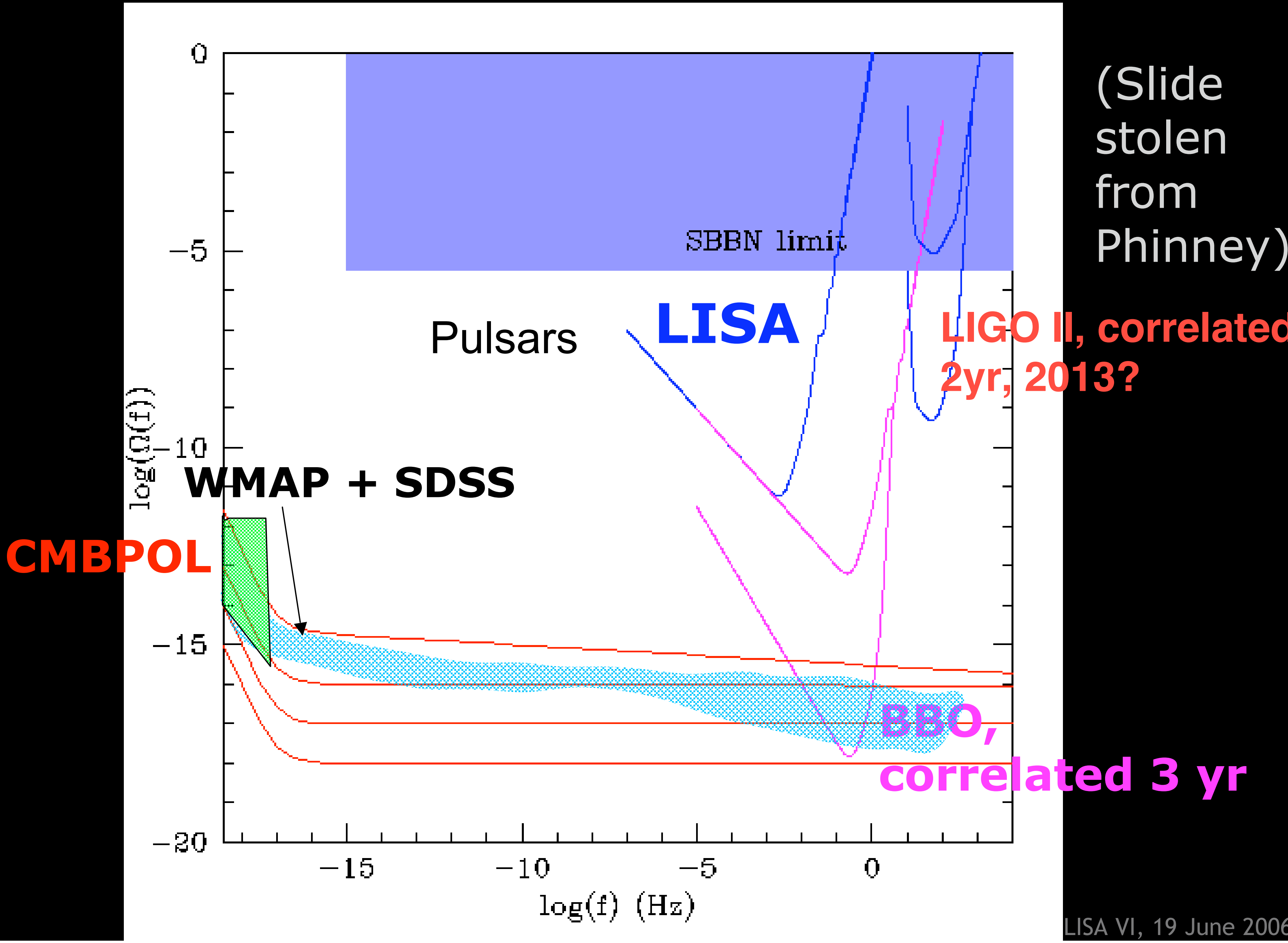
$$g_{ab} = g_{ab}^{\mathrm{FRW}} + h_{ab}(t, \vec{r})$$

Friedmann-Robertson-Walker background

Fluctuations

Measurement of these waves would allow a direct reconstruction of the inflationary potential: *Direct probe of inflation physics*.

Predictions of least contrived scale-free inflation models



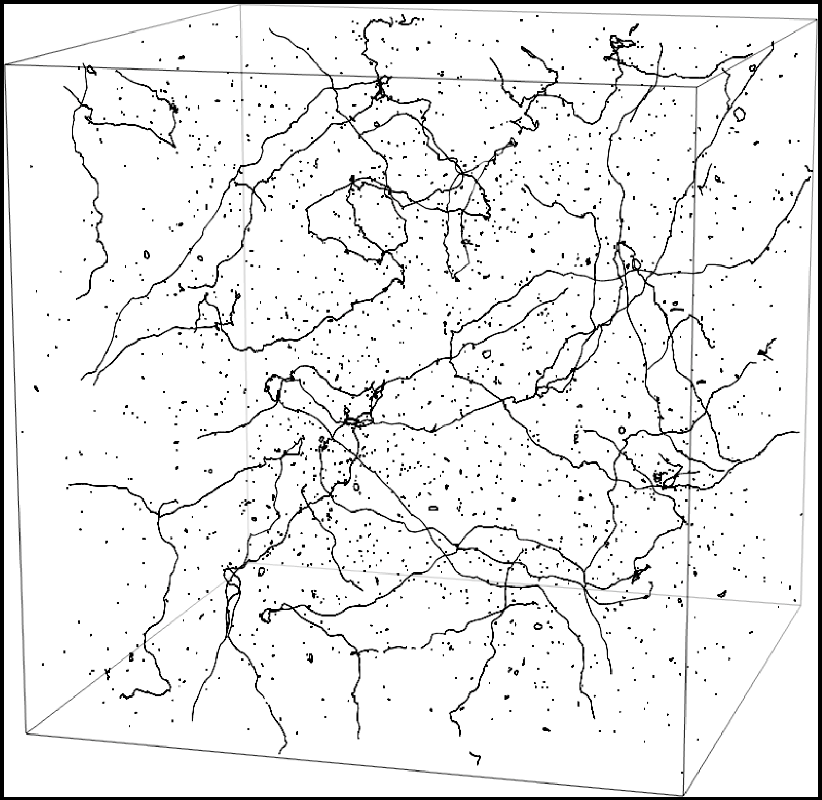
(Slide stolen from Phinney)

Cosmological stochastic backgrounds

As universe cooled, underwent phase transitions as unified interactions separated.

Other models predict production of cosmic strings via phase transitions or during the condensation of our 3 dimensional brane from the early universe dynamics.

Graphic: Bruce Allen, University of Wisconsin-Milwaukee



Strings whirl around at relativistic speeds - can produce GWs much like the cracking of a whip.

Cosmological stochastic backgrounds

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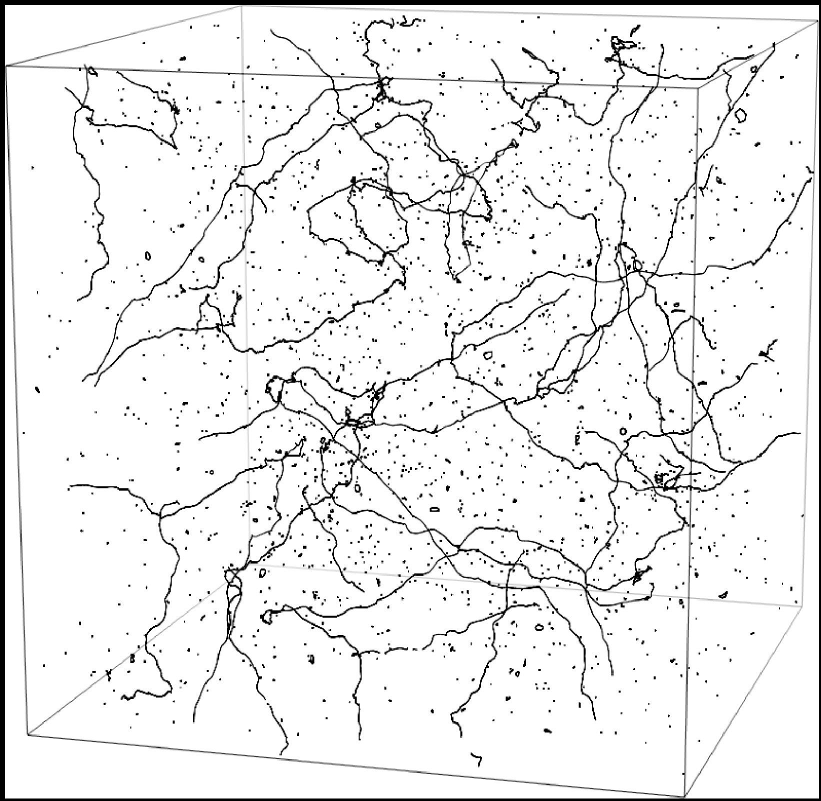


Current results from string theory predict a spectrum that *could* be peaked right in the LISA band.

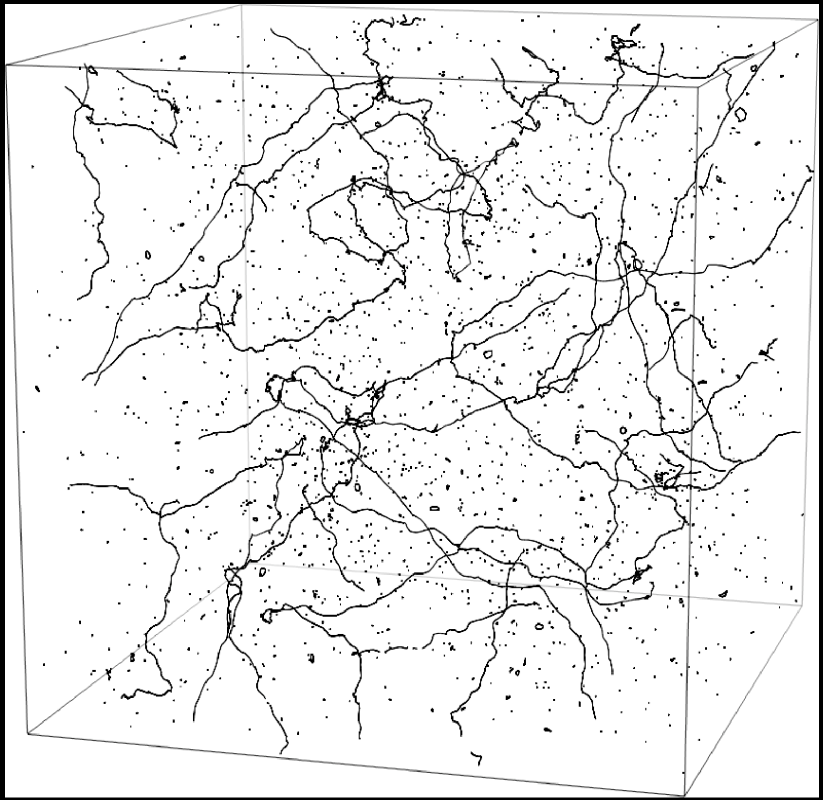
Cosmological stochastic backgrounds

As universe cooled, underwent phase transitions as unified interactions separated.

Models *can* produce signals in LISA band, *if* we get lucky.

Example: Electroweak phase transition expected to have spectrum peaked in LISA band. *If* transition is strongly first order, amplitude will be measureable.

Graphic: Bruce Allen, University of Wisconsin-Milwaukee



Punchline:

LISA has ***NO CHANCE*** of measuring inflationary waves: Simply too weak!

Cosmological background would require us to get lucky with respect to phase transitions; or, realizations of somewhat more speculative ideas.

A lot of discovery space!

Periodic sources

In LISA band: binary star systems, mostly white dwarf binaries.

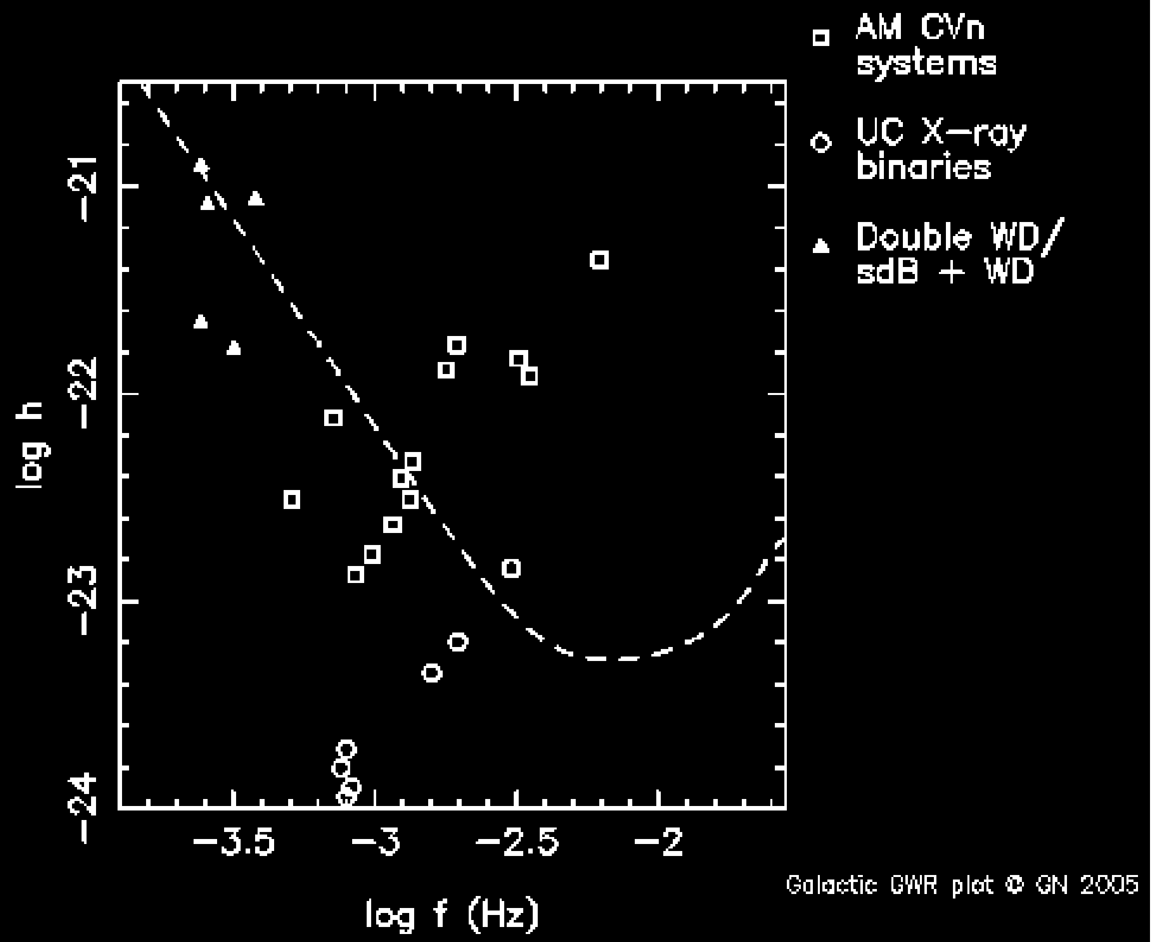
$$\dot{f} = \frac{48}{5\pi}\mathcal{M}^{5/3}(2\pi f)^{11/3}$$

In mass and frequency bands of interest ($M \sim 0.5 - 1$ Msun, $f \sim 10^{-4} - 10^{-2}$ Hz), f changes very little over a multiyear LISA mission - sources are essentially monochromatic.

Periodic sources

Some sources guaranteed!

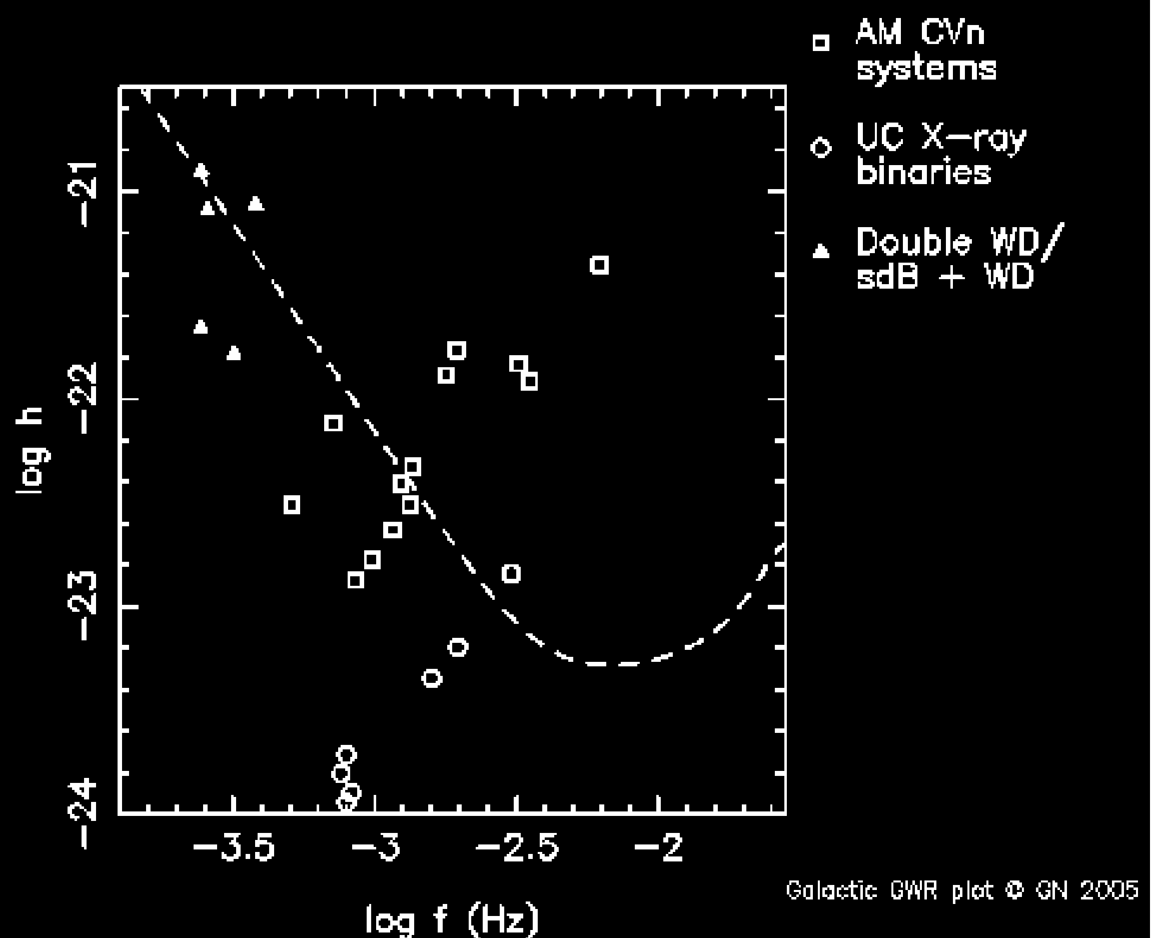
Plot courtesy Gijs Nelemans, shows known compact systems that radiate in the LISA band.



Periodic sources

Some sources guaranteed!

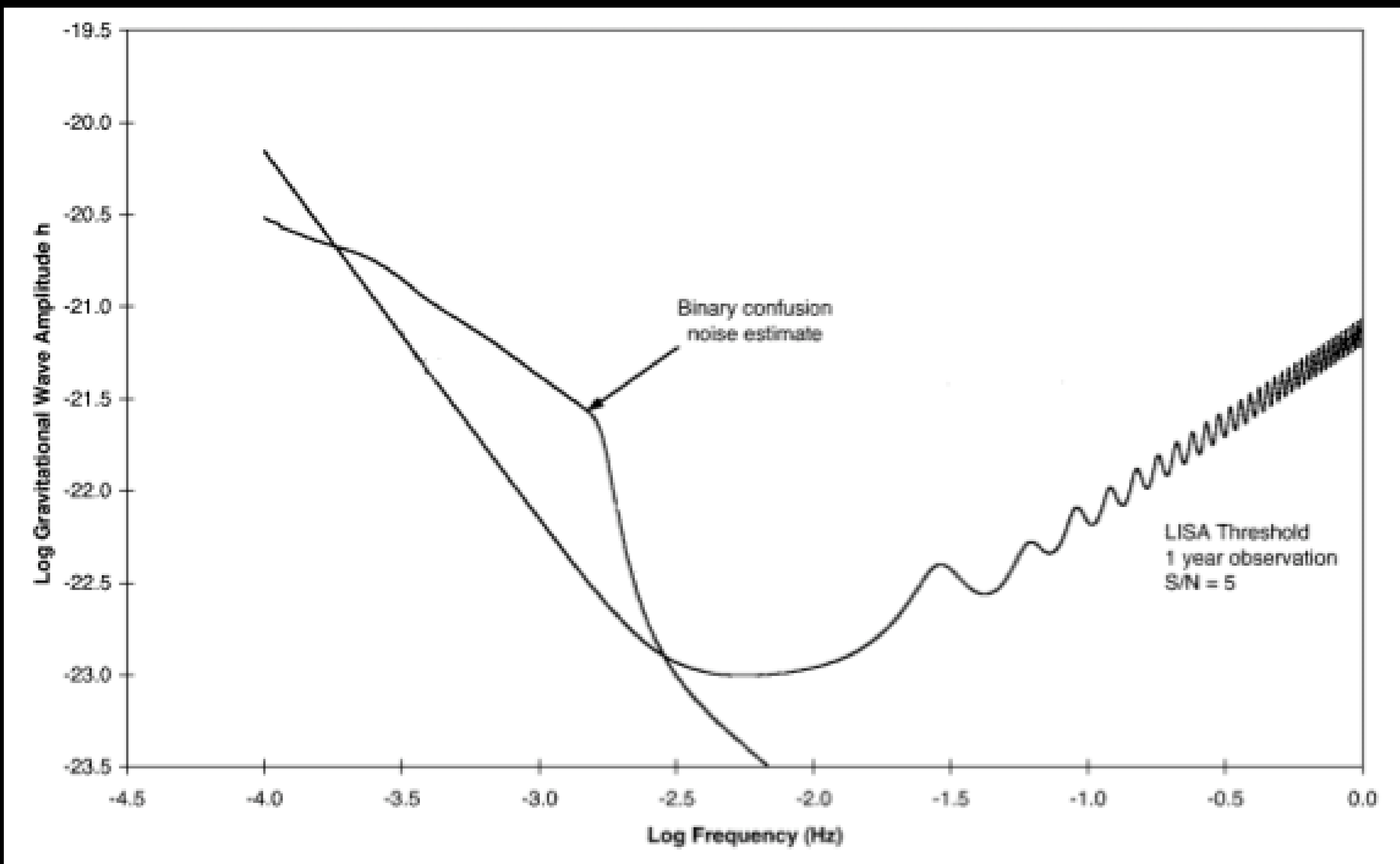
Current status not so well constrained as indicated here: E.g., distance & inclination not well known.



Combined GW/EM observations particularly powerful with these sources.

Periodic 4 Stochastic

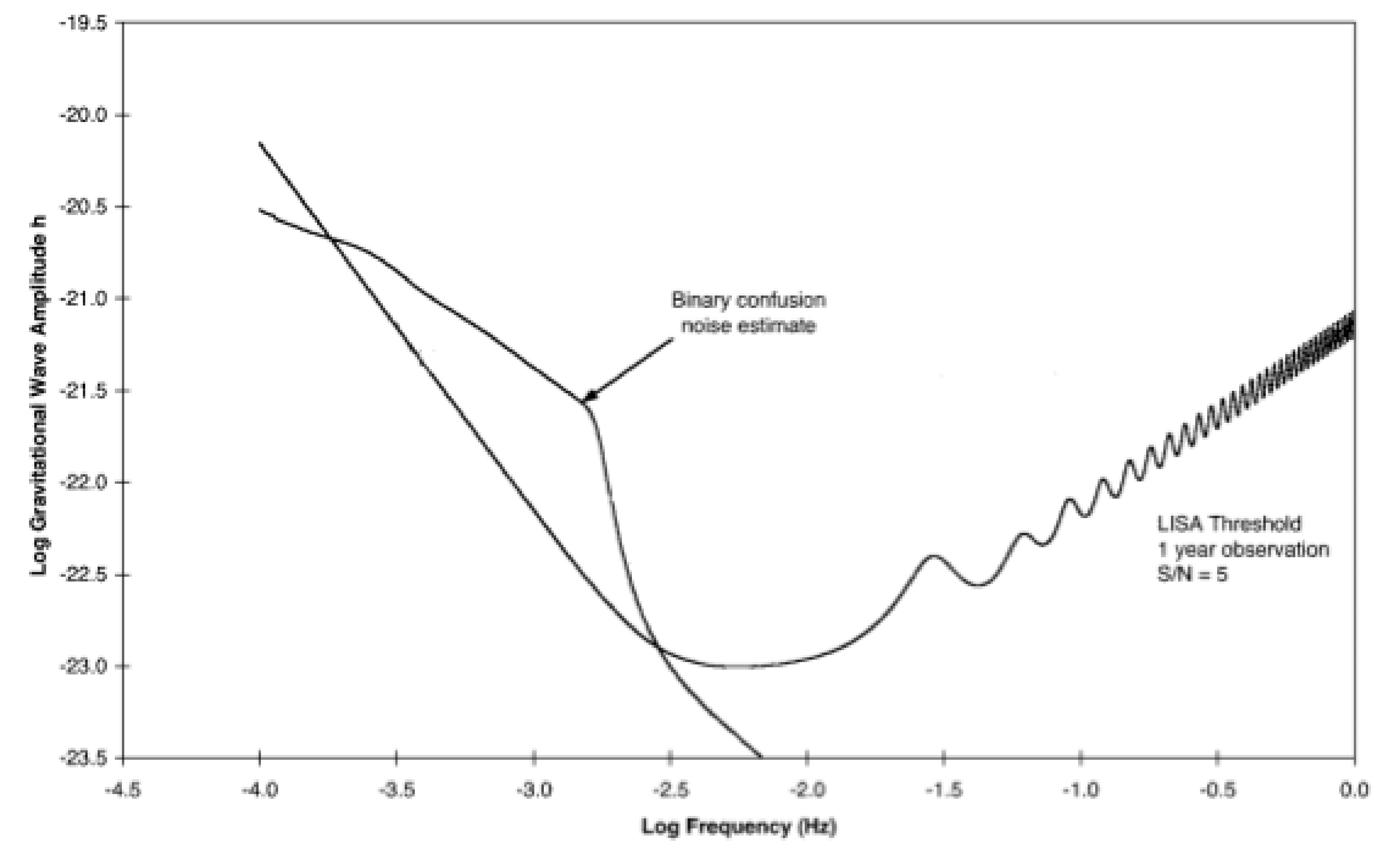
Add model for the distribution of galactic binaries … so numerous that they overlap and form a background!



"Noise" from the viewpoint of studying other GW sources…

Periodic 4 Stochastic

Add model for the distribution of galactic binaries … so numerous that they overlap and form a background!

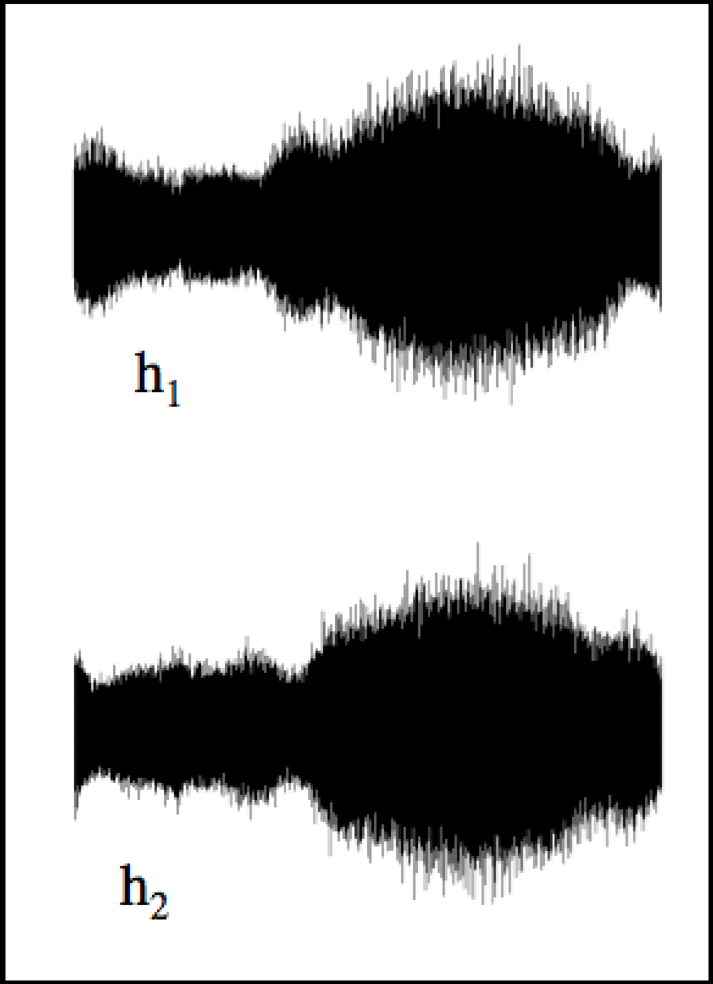


"Signal" if stellar populations is what you want to know about!

Example: Contribution to background of globular cluster NGC 104 (47 Tuc)

Nearby globular cluster with a dense core; contains many binary systems and millisecond pulsars.

Position of cluster + motion of detector imposes unique modulation on waves.

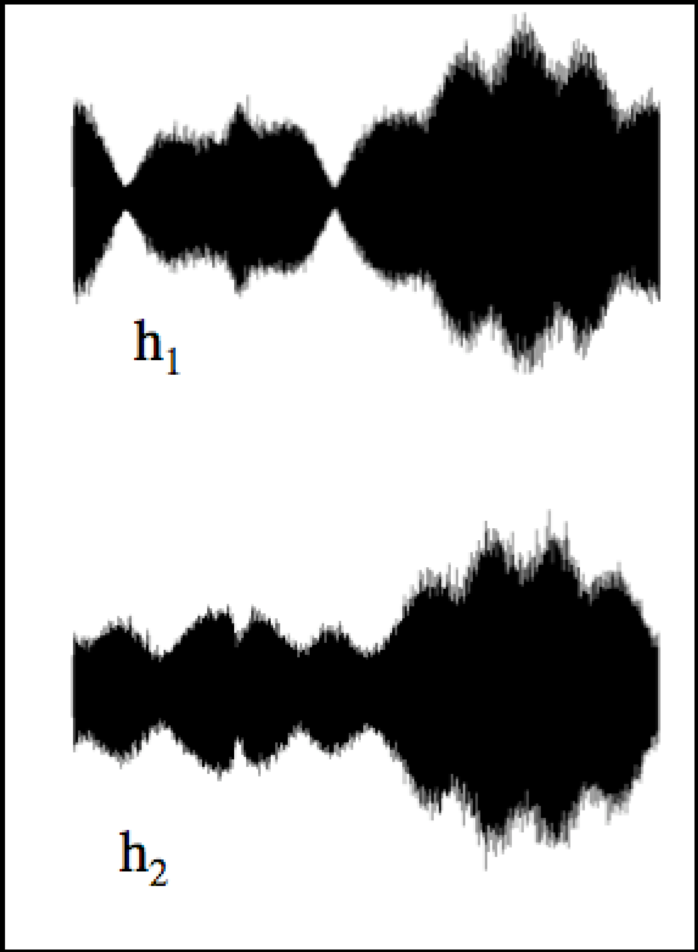


Timeseries shown here!

Population synthesis by Matt Benacquista

Example: Contribution to background of globular cluster NGC 6752

Also nearby, core-collapsed, very high binary fraction in the core (~15 - 40%).



Timeseries shown here!

Population synthesis by Matt Benacquista

Chirping sources: massive BH binaries

Massive binaries produced by *galaxy and halo mergers*.

Mergers are common, especially in the past.

Now known that almost *all* galaxies host a massive black hole ...

Binary black hole formation is *frequent* at these masses!

Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2
PRC97-34a • ST ScI OPO • October 21, 1997 • B, Whitmore (ST ScI) and NASA

Interesting event rate almost certain: At least a few events per year; perhaps hundreds.

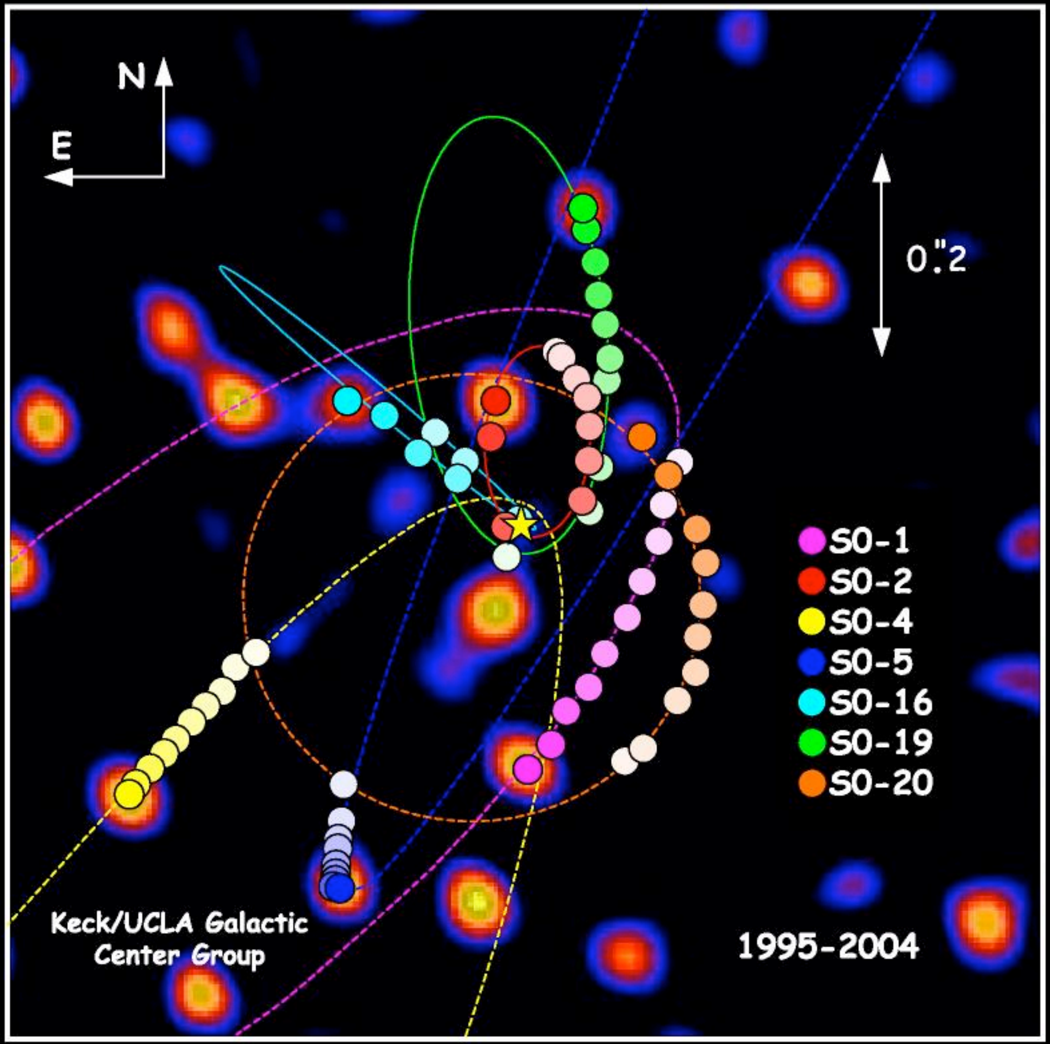
(Haehnelt 1994; Menou, Haiman, & Narayanan 2001; Wyithe & Loeb 2003; Islam, Taylor, & Silk 2004; Sesana et al 2004)

Center of the Milky Way

Orbits of stars in central few light days of the center of our galaxy.

Apply Kepler's laws to these orbits, infer mass:

M = 3.5 x 10^6 Msun

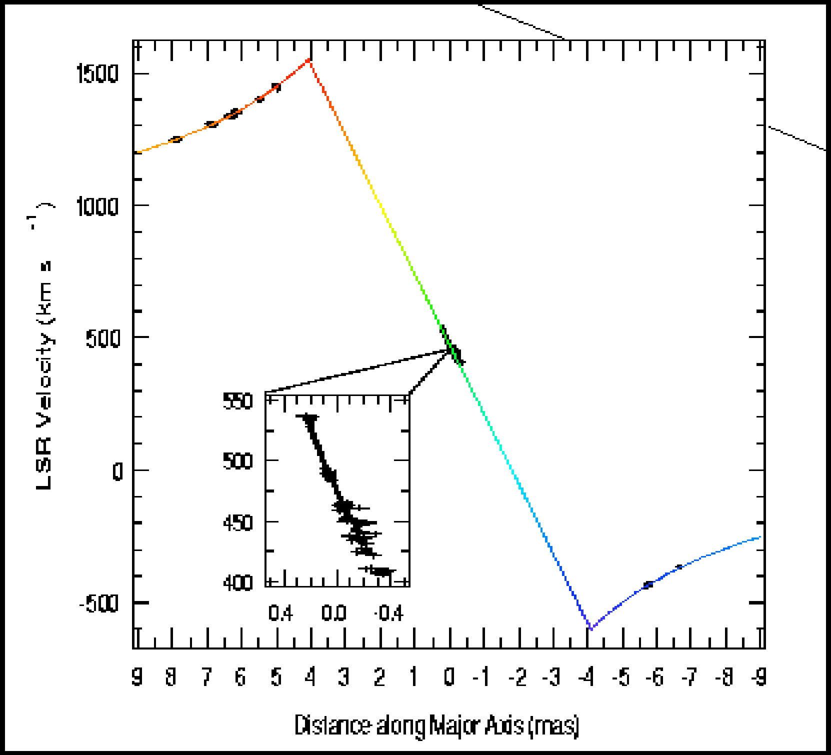


Center of NGC4258 (M106)

Water maser observed in core of Seyfert galaxy, can use to observe orbiting gas.

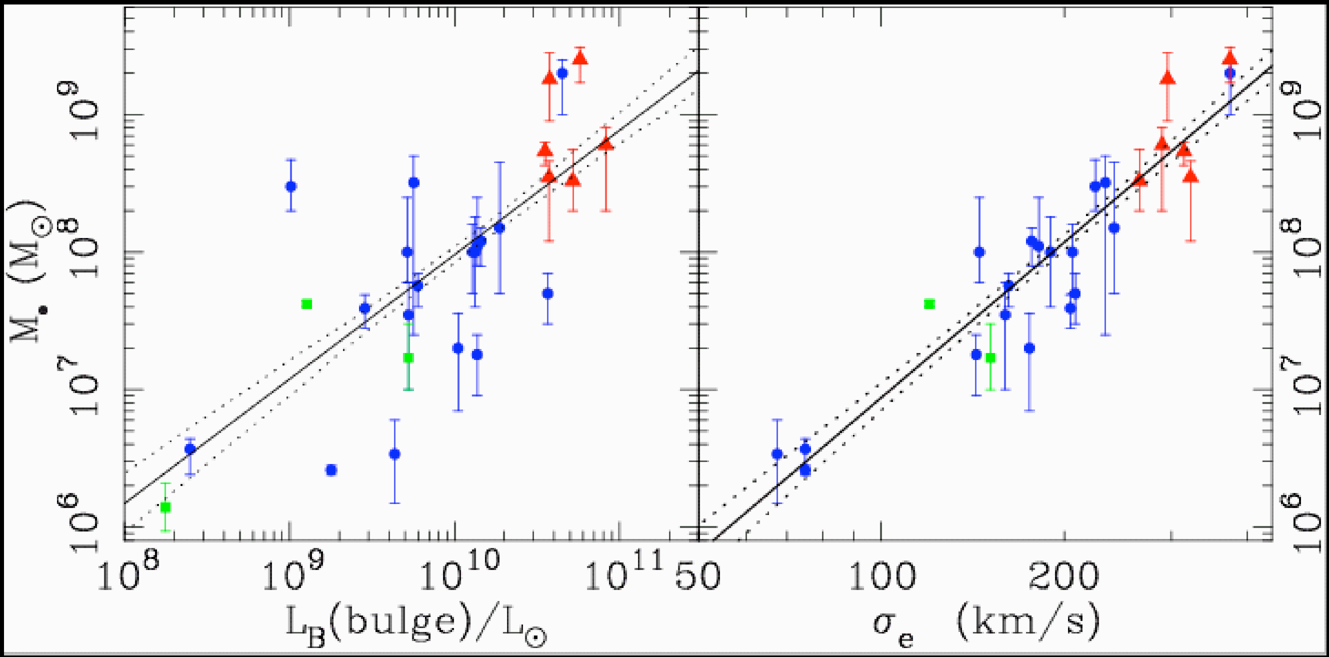
Kepler's law:

M = 3.9 x 10^7 Msun



Property of black holes strongly correlated to properties of galaxies

Trend: "big bulge" = "big black hole".
More precisely: "deep potential well" = "big black hole"



σ: stellar velocity dispersion in galactic bulge.

Implication: The growth of black holes and galaxies is closely related!

Observations and theory: driving us to the conclusion that galaxies (particularly bulges) grow hierarchically …

Natural mechanism to produce binary black holes!

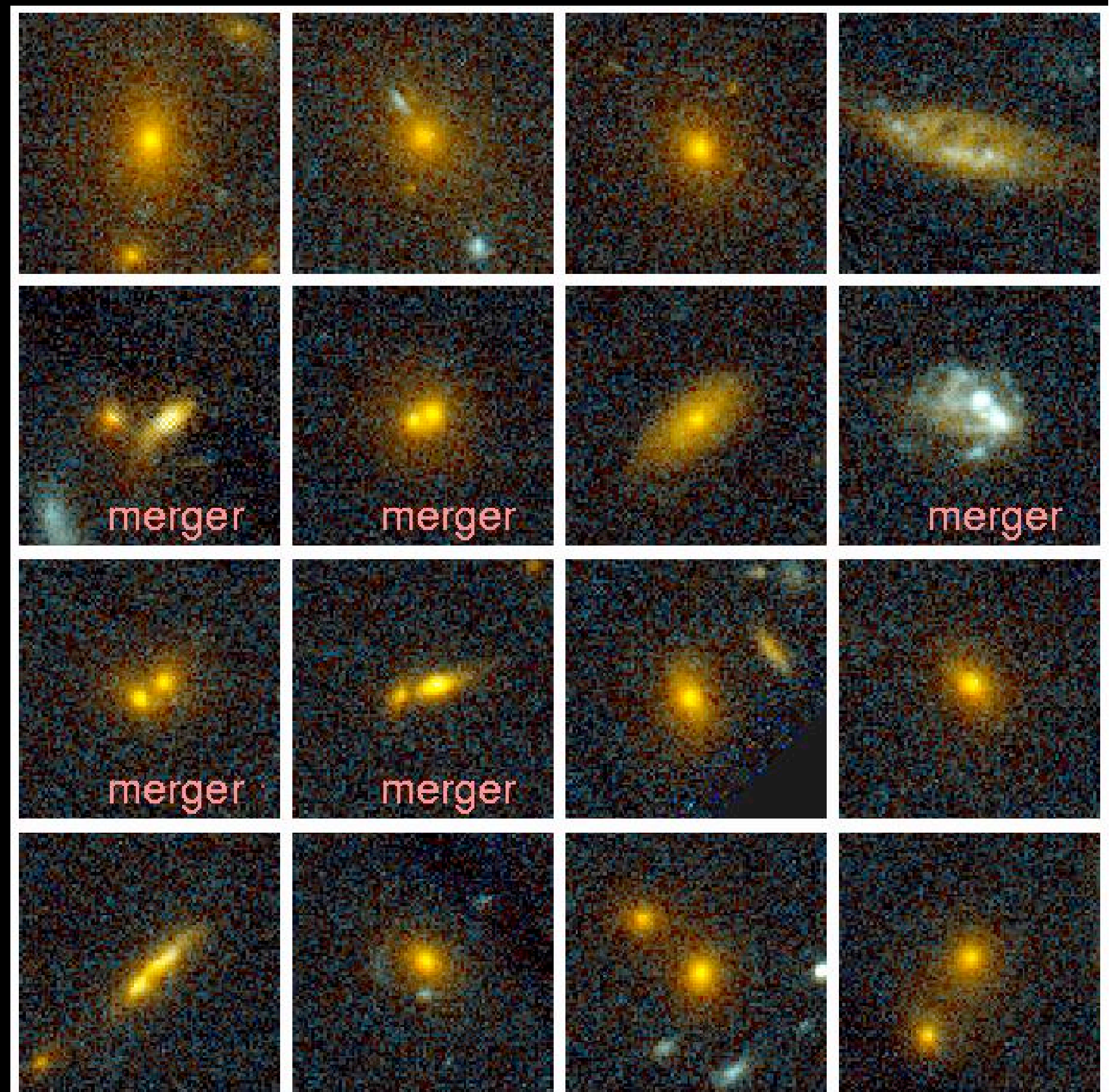
Likely that massive binary black hole formation is a relatively common phenomenon, especially at high z.

Action shot: Mergers at high z

Mergers in rich cluster MS 1054-03 ($z = 0.83$)

Shown: 16 brightest galaxies. ***About 20% are merging!***

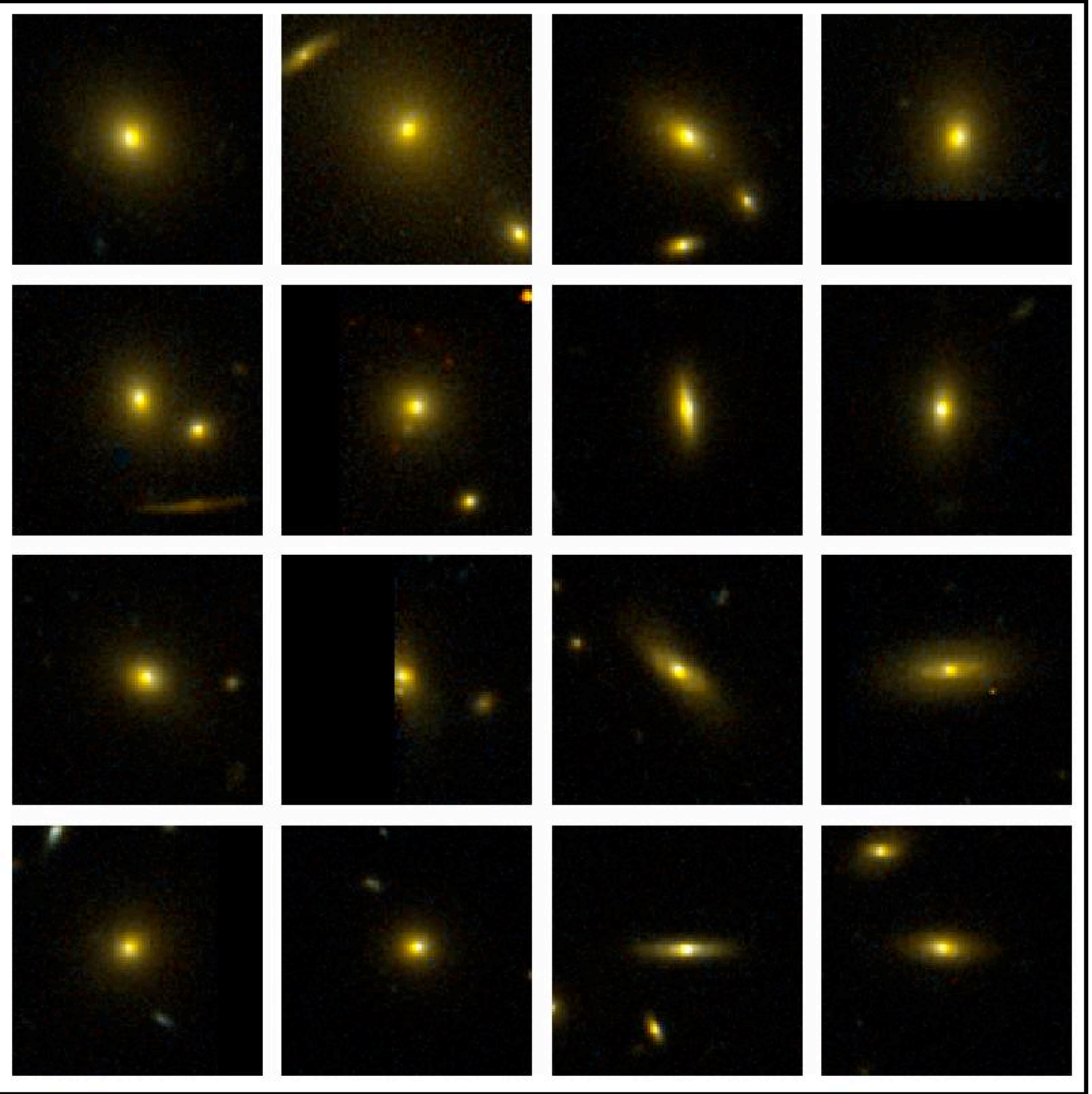
van Dokkum et al 1999, ApJ 520, L95.



Inaction shot: No mergers at low z

Essentially no mergers seen in MS 1358-62 (z = 0.32)

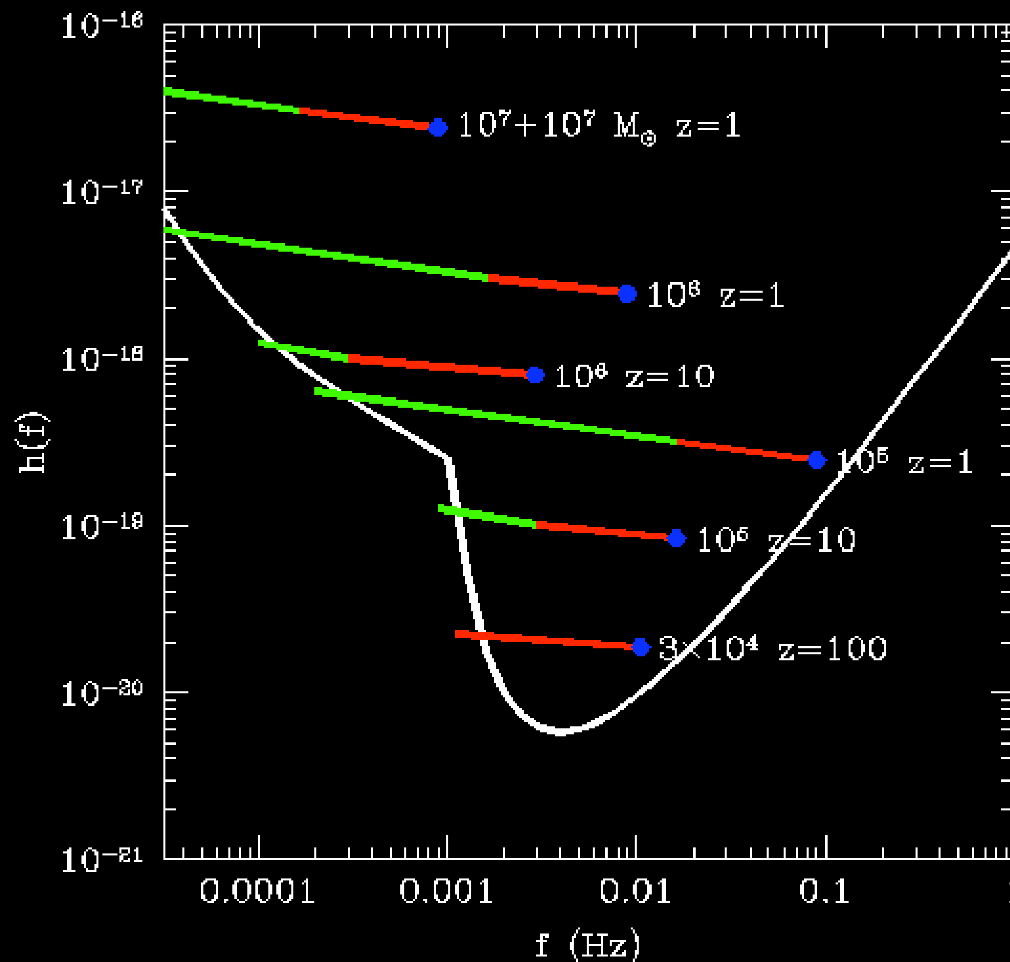
Shown: 16 brightest galaxies. ***No apparent mergers!***



van Dokkum et al 1999, ApJ 520, L95.

Binary black hole waves: VERY high SNR!

In relevant mass and redshift range [10^5 Msun $< (1 + z)M_{total} <$ 10^7 Msun out to z ~ 10 or so], integrated signal to noise ratio can be as high several hundred or a few thousand.



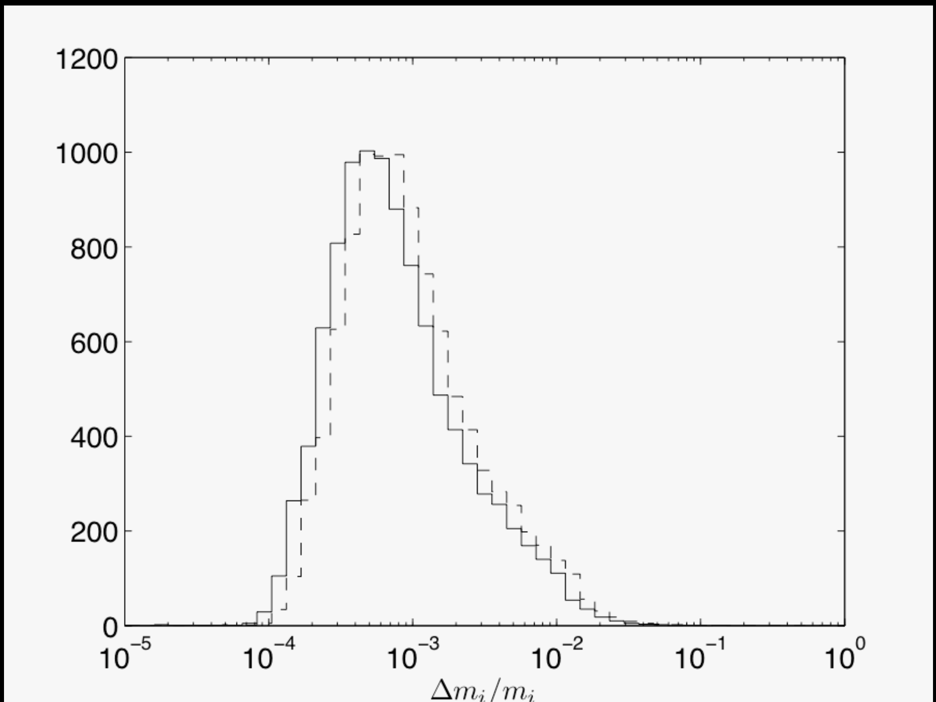
Binary black hole waves vs LISA noise spectrum

Can precisely measure binary parameters!

What waves measure

Very accurately determine "intrinsic" parameters which set the orbital phase: Masses of the members of the binary, magnitude of their spins.

Monte Carlo: 10^4 binaries at $z = 1$, 10^6 Msun going into 3×10^6 Msun; spin precession taken into account, with random spins, spin orientations, and sky positions; errors estimated using maximum likelihood computation of Fisher matrix. (Lang & Hughes, in prep.)



Individual black hole masses determined with ~0.1% accuracy.

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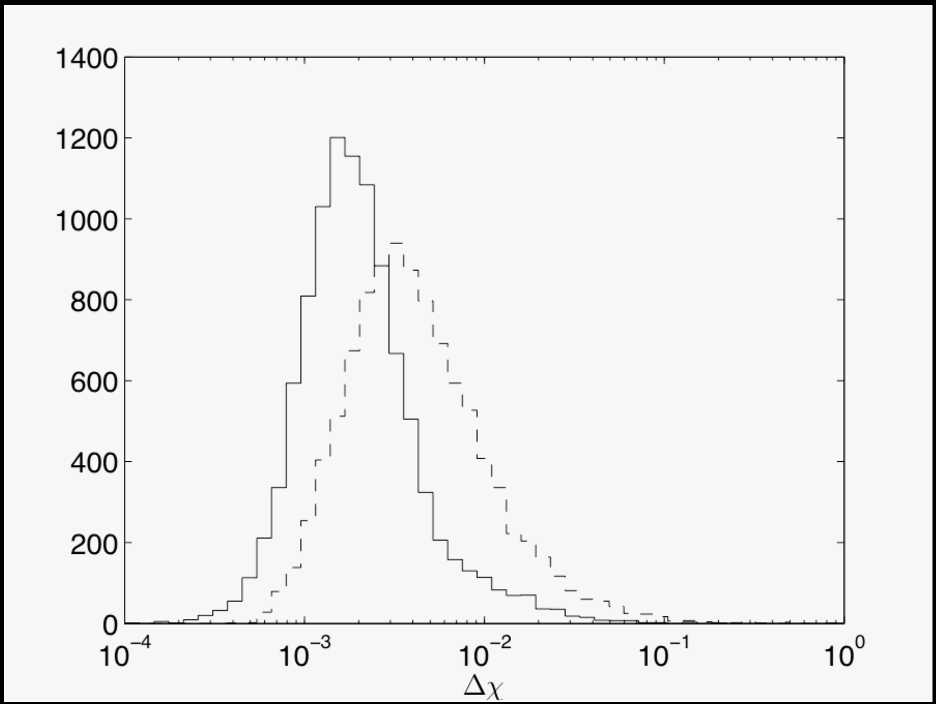
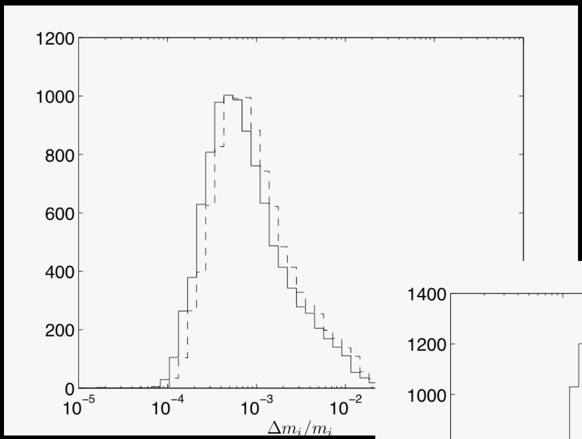


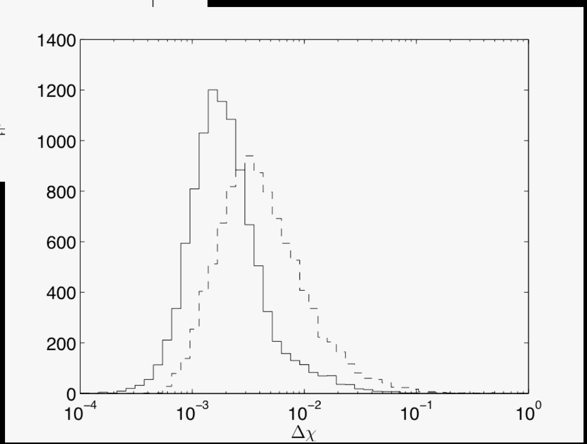
Individual black hole spins determined with (0.1-1)% accuracy.

What waves measure

Very accurately determine "intrinsic" parameters which set the orbital phase: *Masses* of the members of the binary, magnitude of their spins.

Monte Carlo: 10^4 binaries at z = 1, 10^6 Msun going into 3 x 10^6 Msun; spin precession taken into account, with random spins, spin orientations, and sky positions; errors estimated using maximum likelihood computation of Fisher matrix. (Lang & Hughes, in prep.)



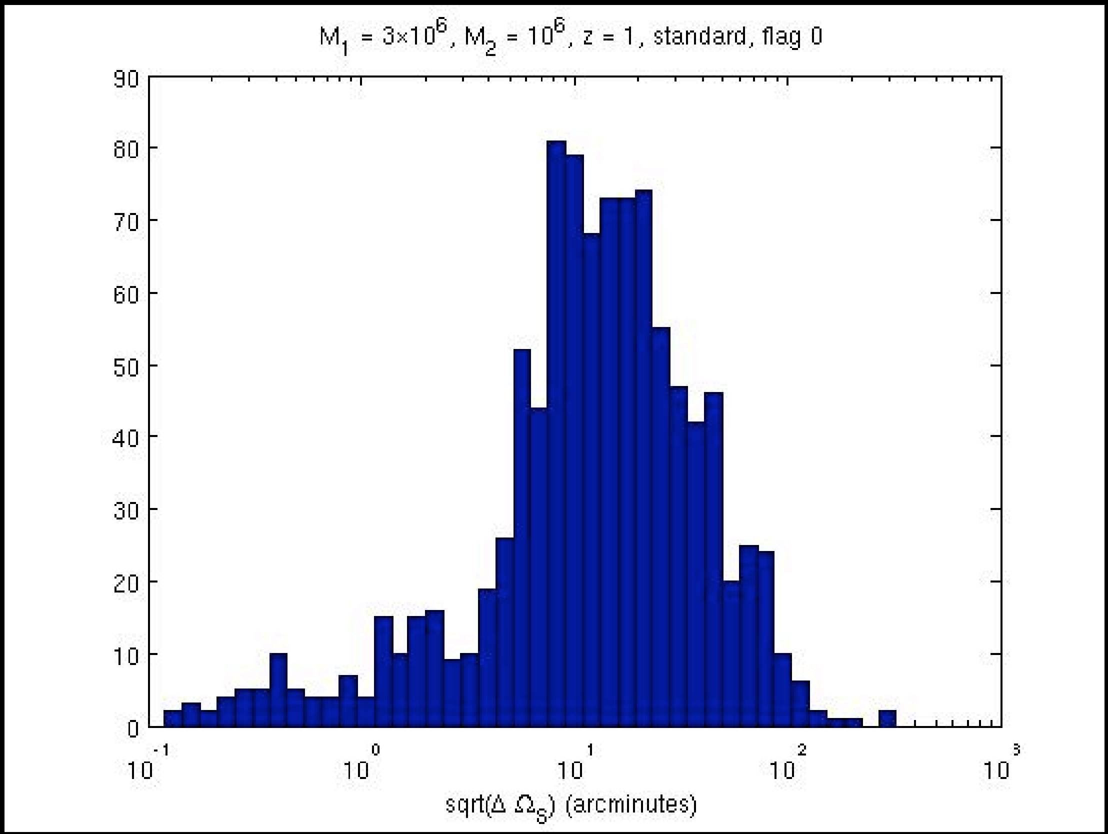


LISA is a tool for precisely mapping the cosmic growth of black hole mass and spin!

What waves measure

Also determine "extrinsic" parameters: position of the binary on the sky, its orientation, distance from the solar system.

Same Monte Carlo setup as for intrinsic parameters.

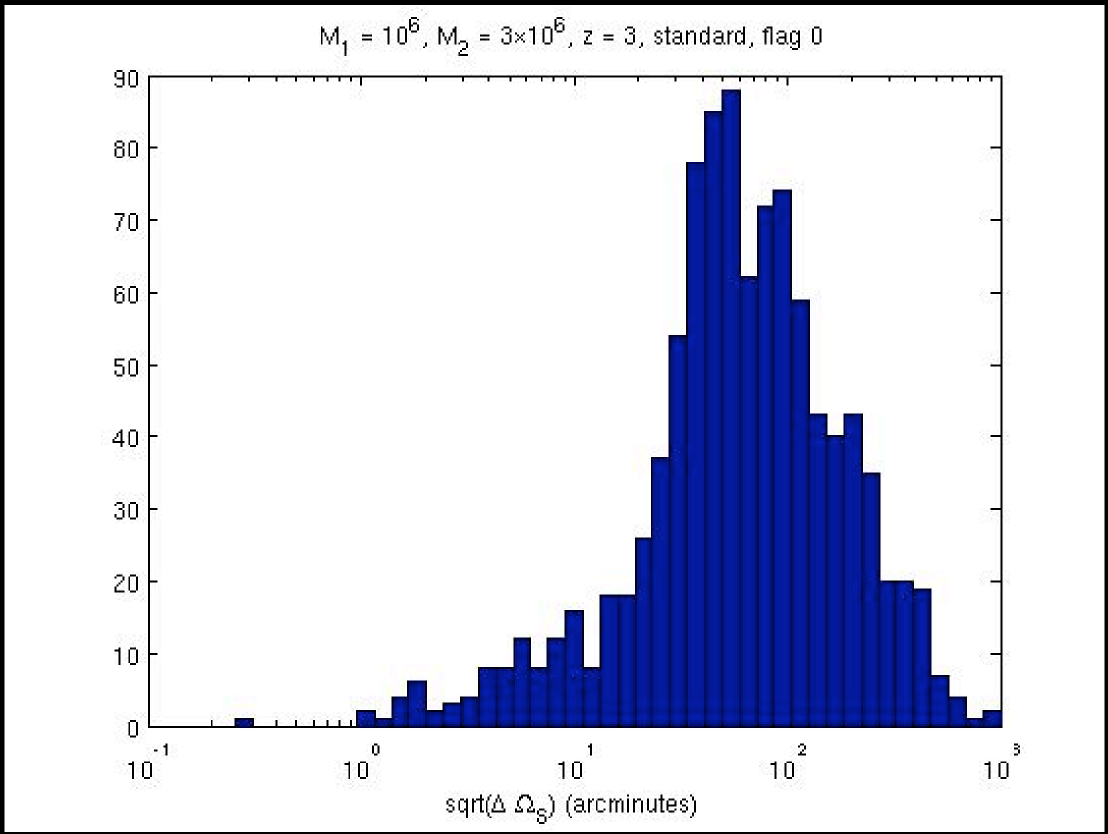


Size of the spot to which binary is localized isn't terrible at low *z* - a few to a few 10s of arcminutes.

What waves measure

Also determine "extrinsic" parameters: position of the binary on the sky, its orientation, distance from the solar system.

Same Monte Carlo setup, but now at z = 3.

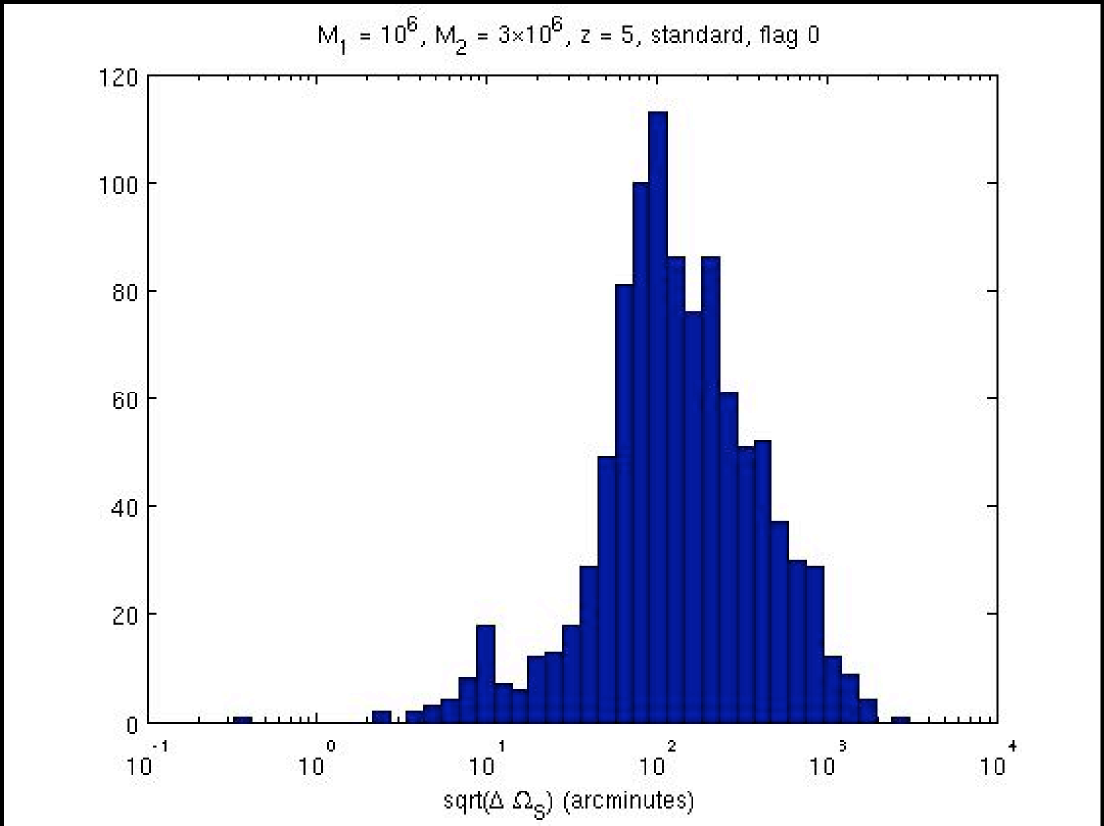


Spot grows considerably as we move to higher redshift: at z = 3, typically ~3 times larger than at z = 1.

What waves measure

Also determine "extrinsic" parameters: position of the binary on the sky, its orientation, distance from the solar system.

Same Monte Carlo setup, but now at $z = 5$.



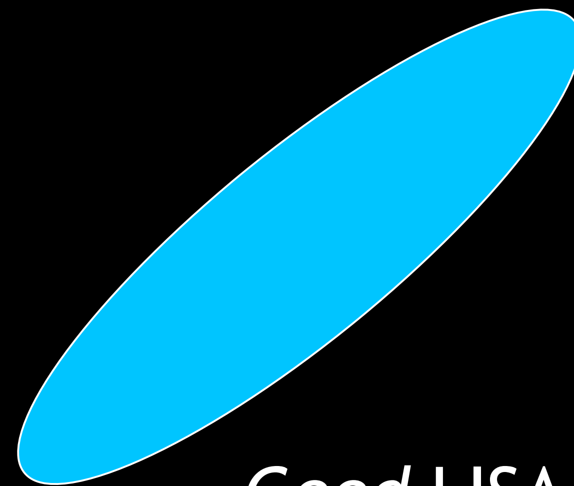
Spot grows considerably as we move to higher redshift: at $z = 5$, typically ~3 times larger than at $z = 3$.

The LISA "pixel"

Full moon:
~30 arcminutes.

The LISA "pixel"

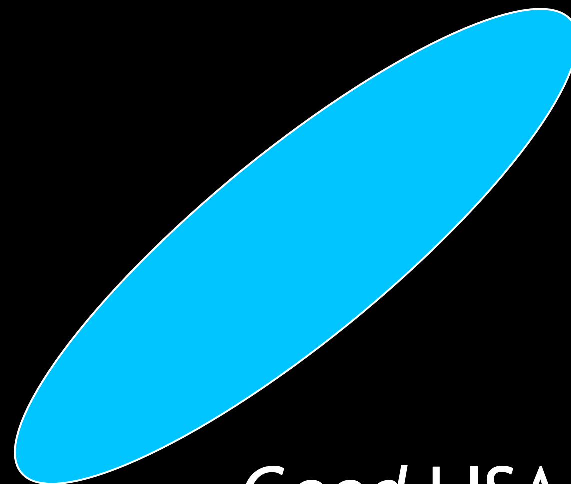
Full moon:
~30 arcminutes.



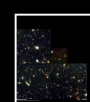
Good LISA pixel: A few 10s of arcminutes along major axis, ~10 along minor axis.

The LISA "pixel"

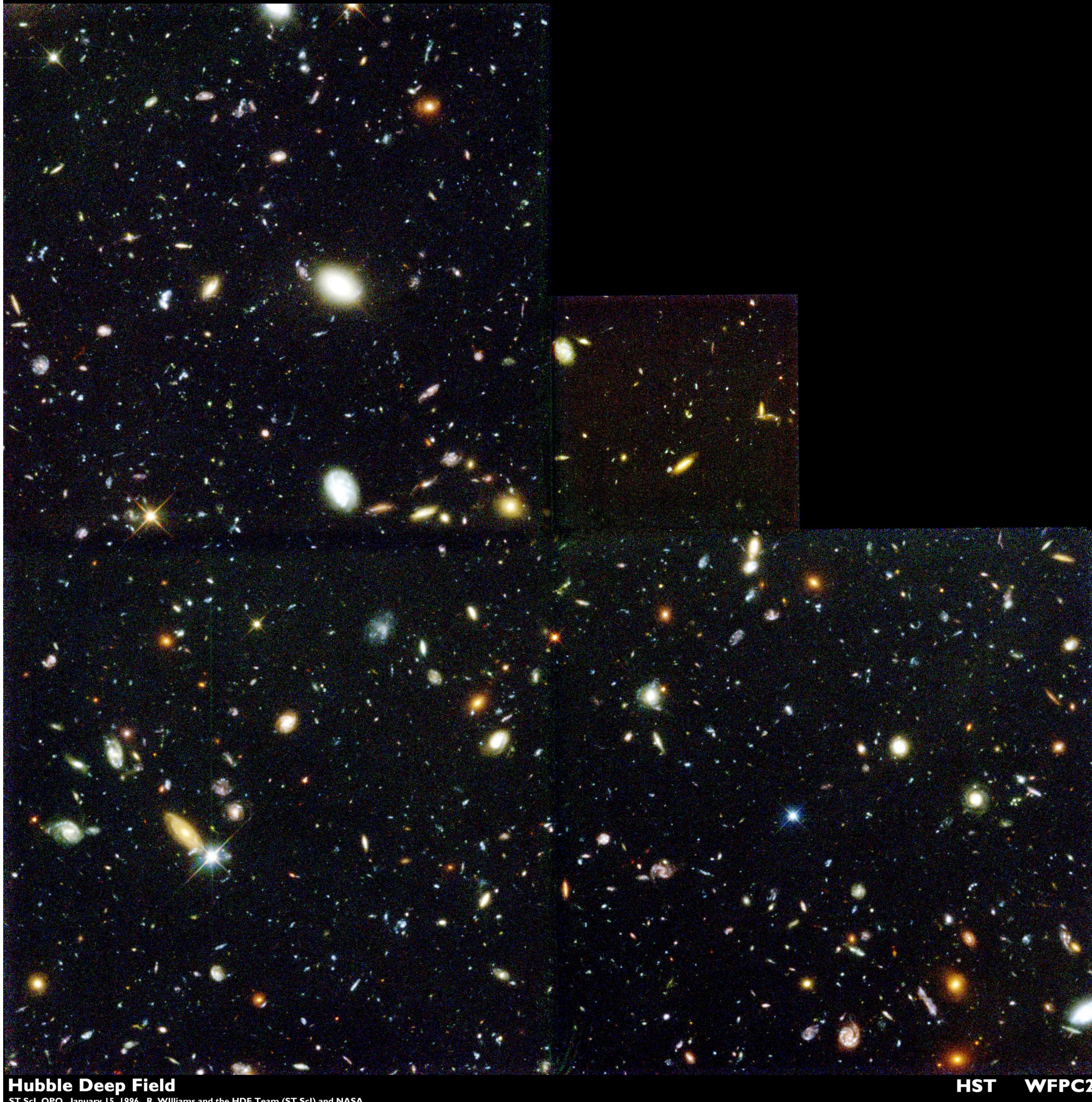
Full moon:
~30 arcminutes.



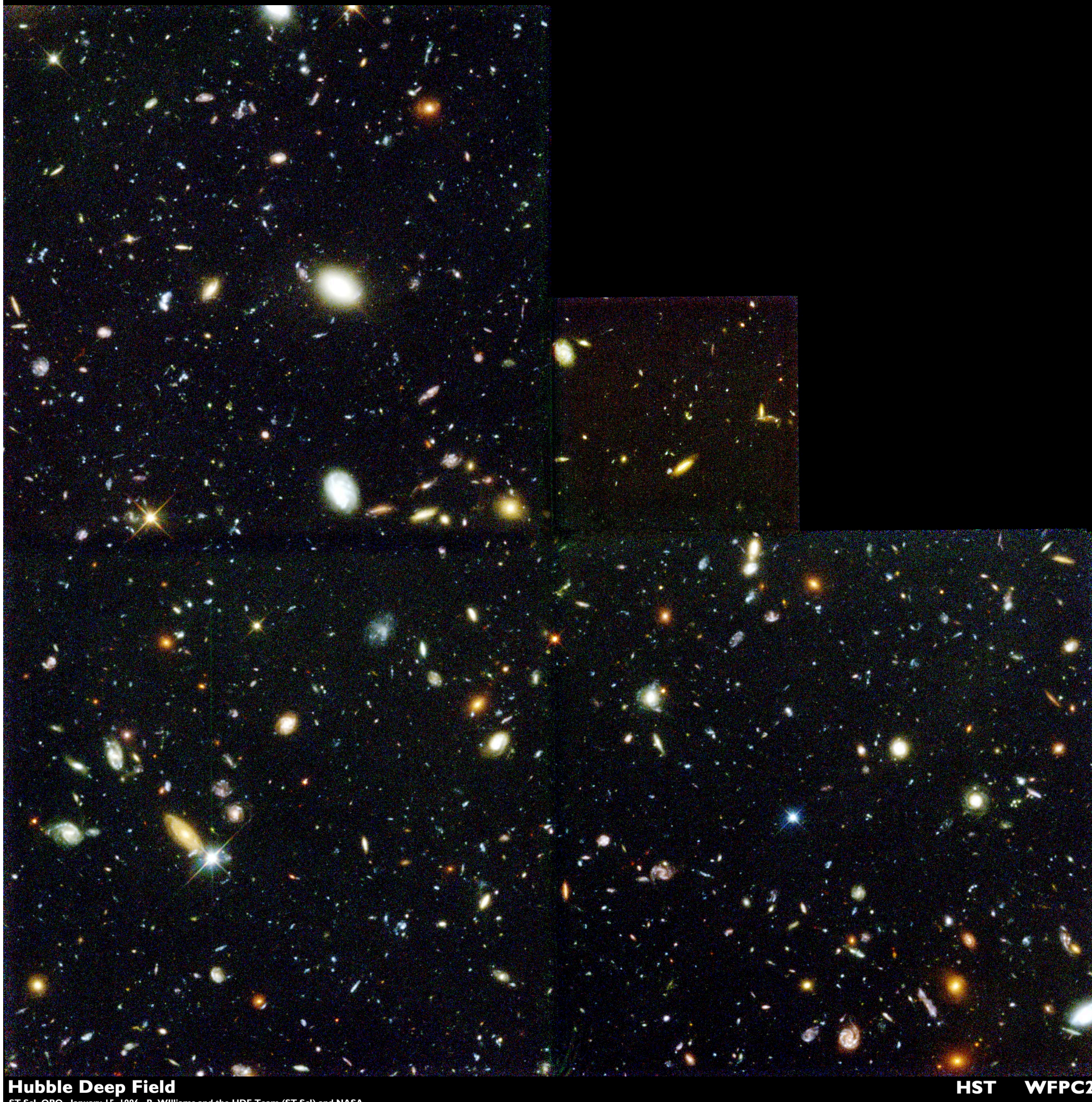
Good LISA pixel: A few 10s of arcminutes along major axis, ~10 along minor axis.



The Hubble Deep Field:
144 arcseconds.



Imagine trying to find *the* galaxy that hosts a merger in a "pixel" 50 times larger than this!



Imagine trying to find *the* galaxy that hosts a merger in a "pixel" 50 times larger than this!

(Not quite so grim since we'll have redshift info … but still will want to narrow the search space considerably.)

Does something go "bang"?

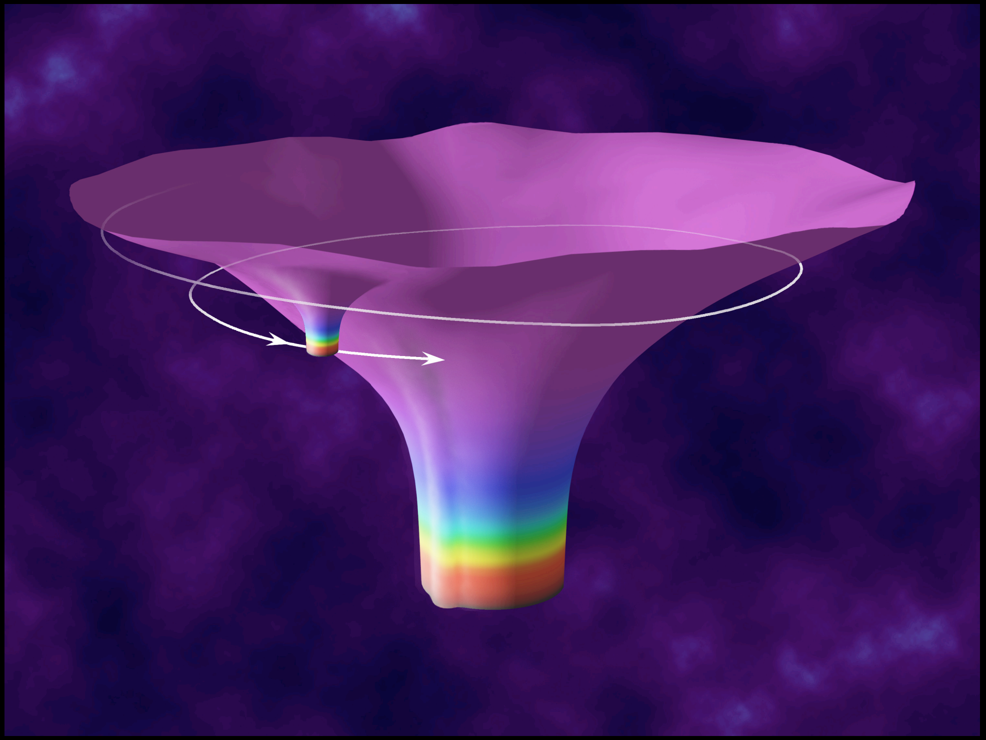
Ideal situation: some kind of electromagnetic signature associated with merger - provides a counterpart, making it possible to pin down location of host galaxy very precisely.

Big question: If some activity happens during the merger process, ***does it temporally coincide with the LISA signal***?

If not, might need to just look for morphologically consistent galaxies in the LISA pixel.

Really complicated chirping sources: EMRIs - Extreme mass ratio inspiral

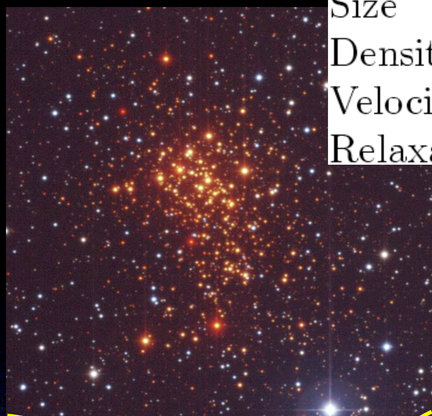
The relativist's favorite source! Extreme mass ratio means spacetime mostly determined by large body: "Clean" probe into black hole spacetimes



Binaries which produce EMRI events formed by dynamical scattering processes in the nuclei of galaxies; talk by Clovis Hopman on Weds.

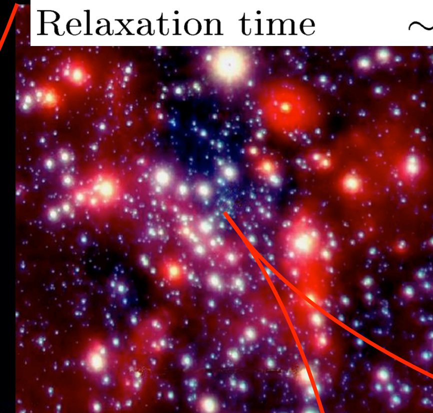
The setting (courtesy Marc Freitag)

Stellar cluster

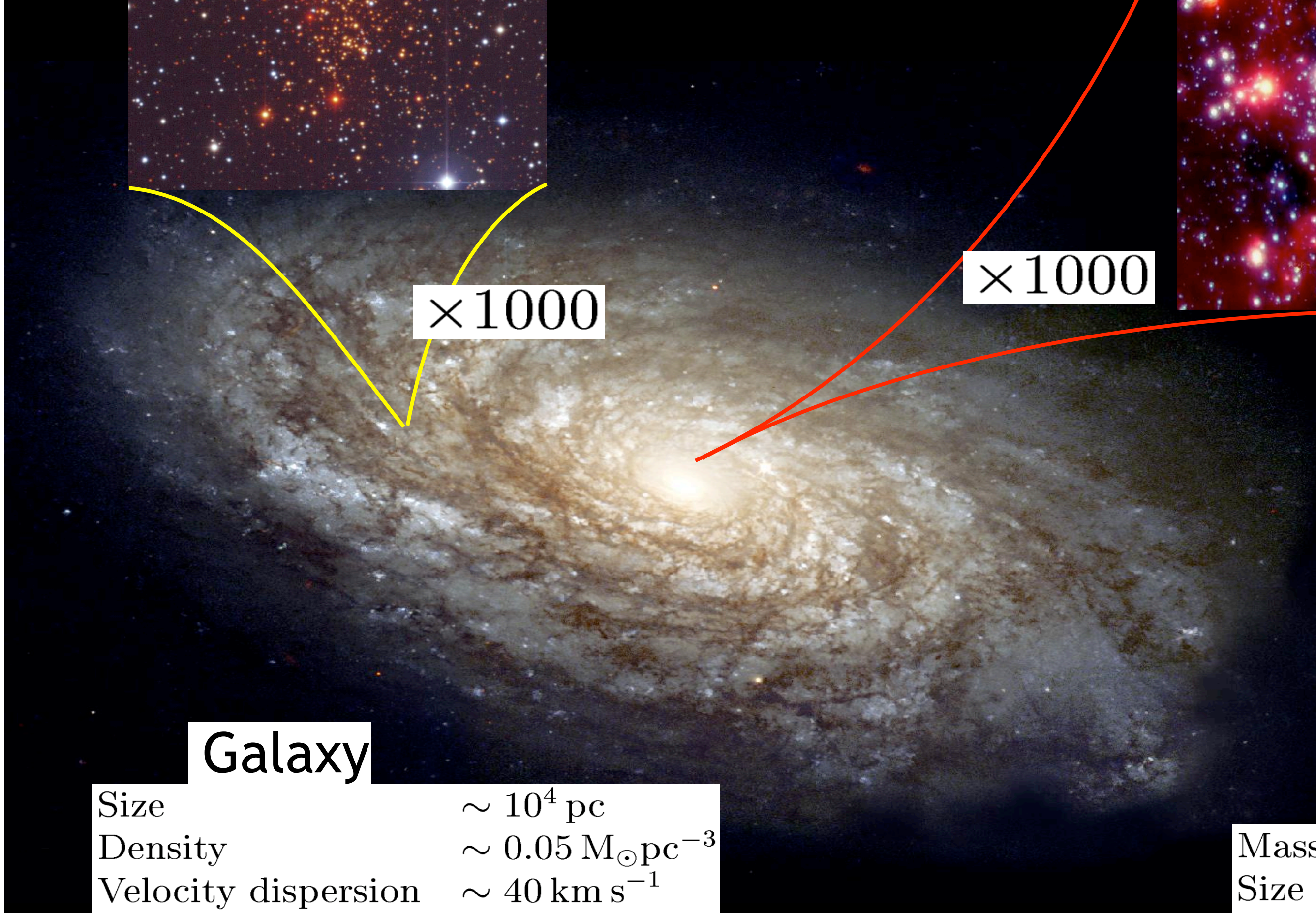


Size	$\sim 1-10\,\mathrm{pc}$
Density	$\sim 10^{3-6}\,\mathrm{M_\odot pc^{-3}}$
Velocity dispersion	$\sim 10-20\,\mathrm{km\,s^{-1}}$
Relaxation time	$\sim 10^{7-9}$ years

Galactic nucleus

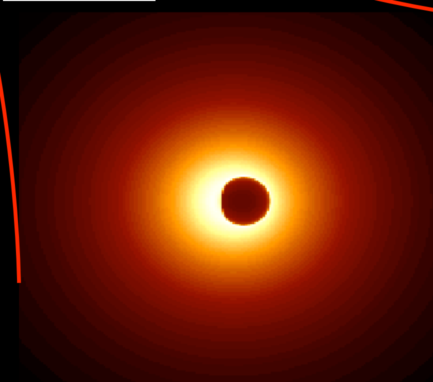


Size	$\sim 1-10\,\mathrm{pc}$
Density	$\sim 10^{7}\,\mathrm{M_\odot pc^{-3}}$
Velocity dispersion	$\sim 100-1000\,\mathrm{km\,s^{-1}}$
Relaxation time	$\sim 10^{8-9}$ years



Galaxy

Size	$\sim 10^{4}\,\mathrm{pc}$
Density	$\sim 0.05\,\mathrm{M_\odot pc^{-3}}$
Velocity dispersion	$\sim 40\,\mathrm{km\,s^{-1}}$
Relaxation time	$\sim 10^{15}$ years



Massive Black Hole

Mass	$10^{6-9}\,\mathrm{M_\odot}$
Size	$R_\mathrm{S} = 2GM_\mathrm{BH}/c^2 = 10^{-7} - 10^{-4}\,\mathrm{pc}$
Rotation	??

Key issue: Getting compact objects into region of "loss cone"

Region of phase space in which smaller object becomes bound strongly enough that radiation emission dominates its orbit evolution.

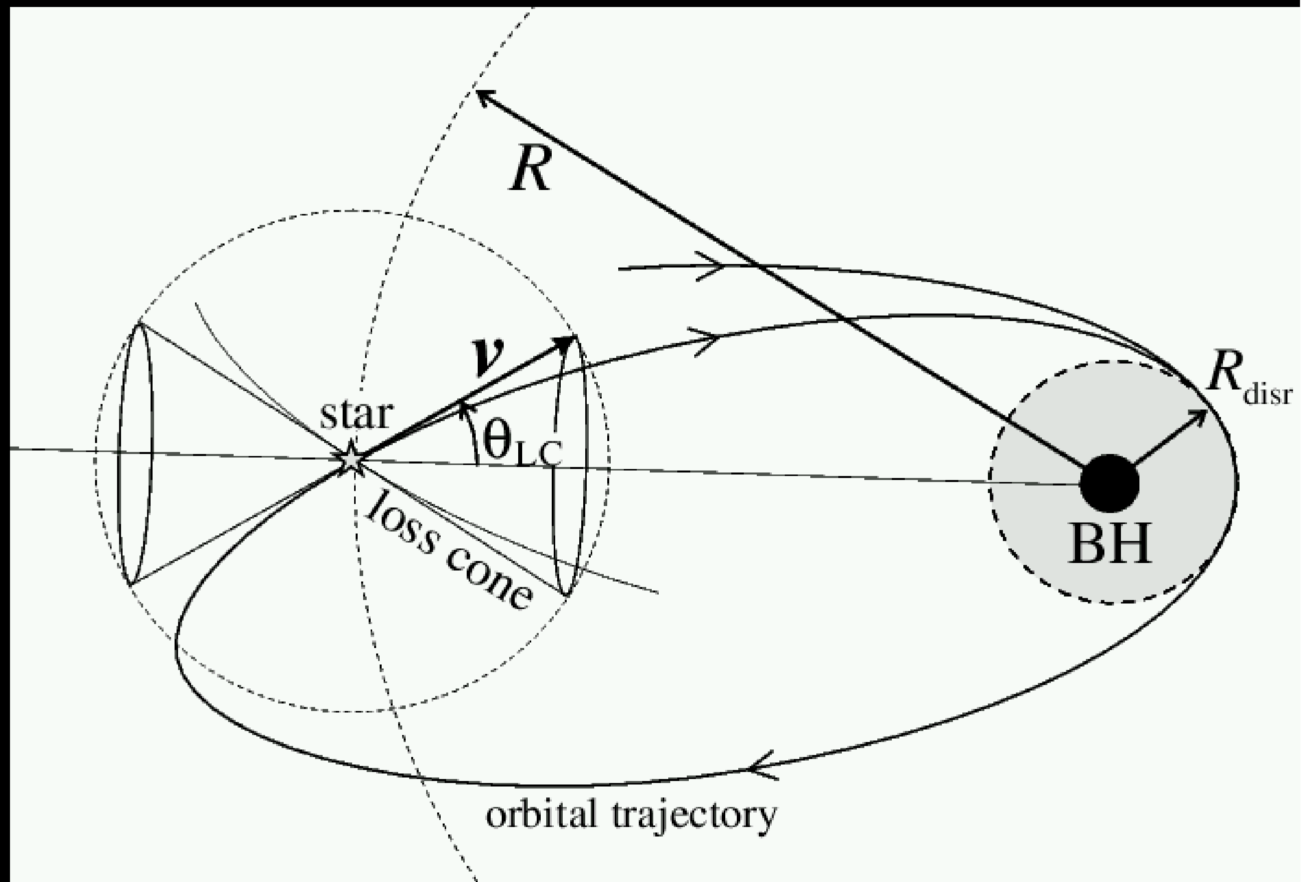
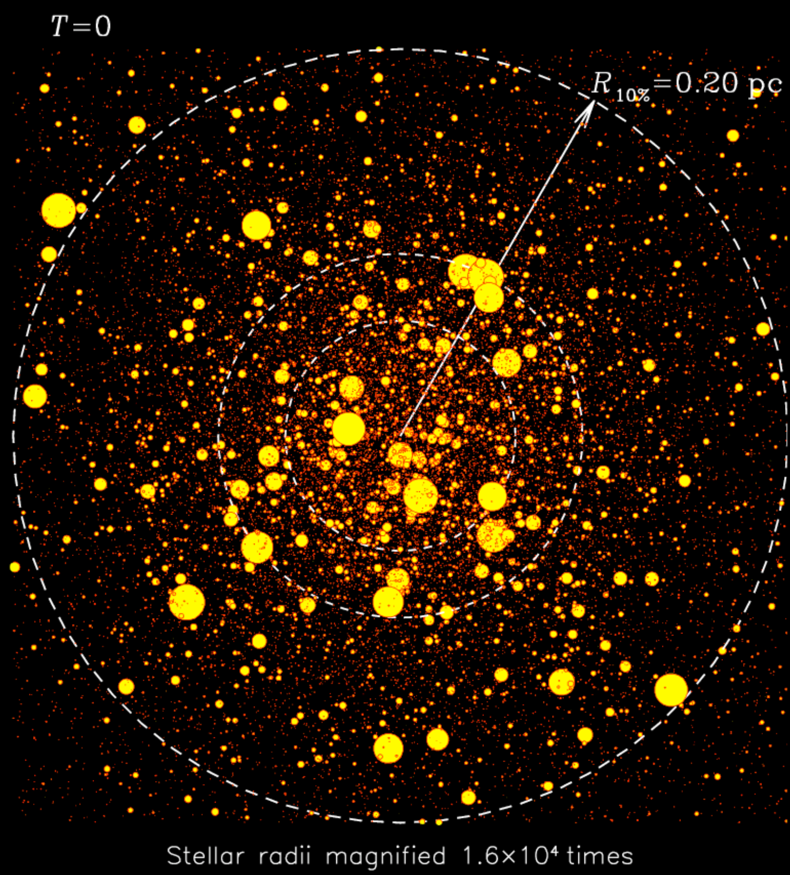


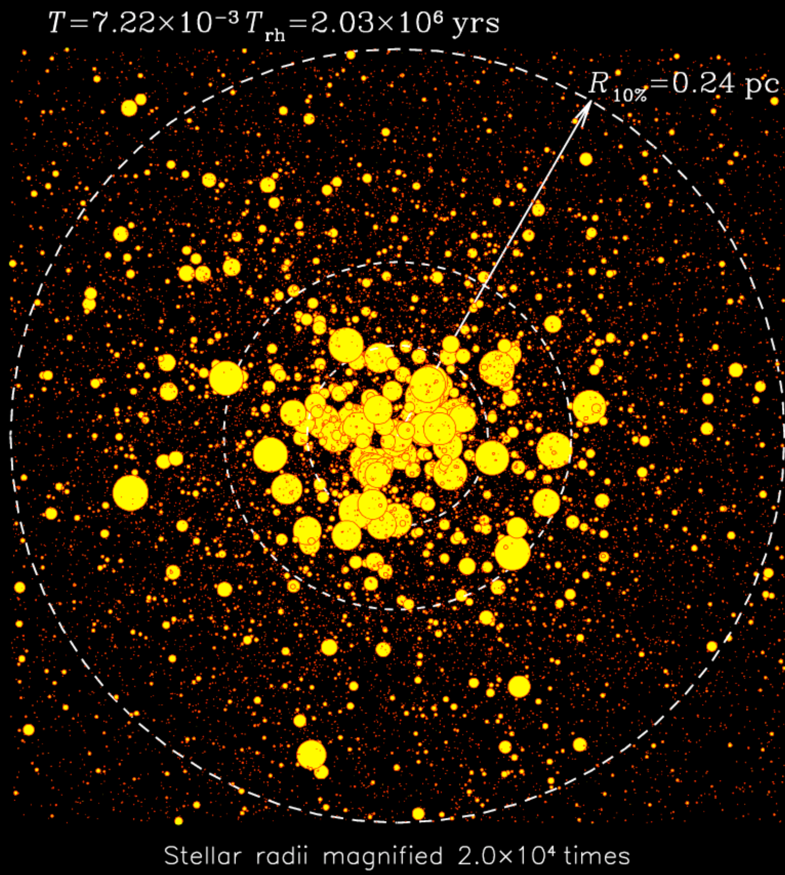
Image courtesy Marc Freitag

Key phenomenon: Mass segregation

Initial conditions



Core collapse

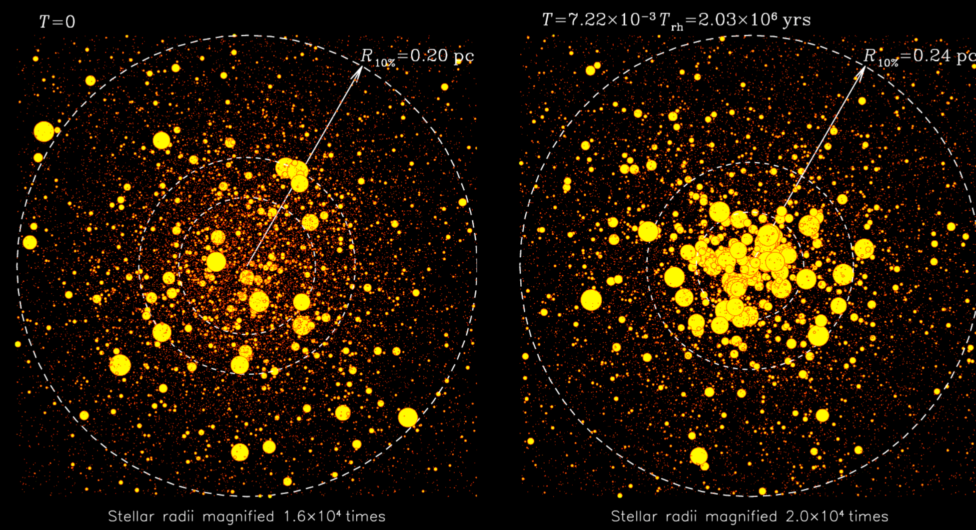


Basic idea quite simple: equipartition of kinetic energy; most massive objects sink.

Gürkan, Freitag & Rasio 2004; Freitag, Rasio & Baumgardt 2005

Key phenomenon: Mass segregation

For EMRI problem, mass segregation implies that the secondaries which are most likely to be scattered into loss cone are stellar mass black holes.



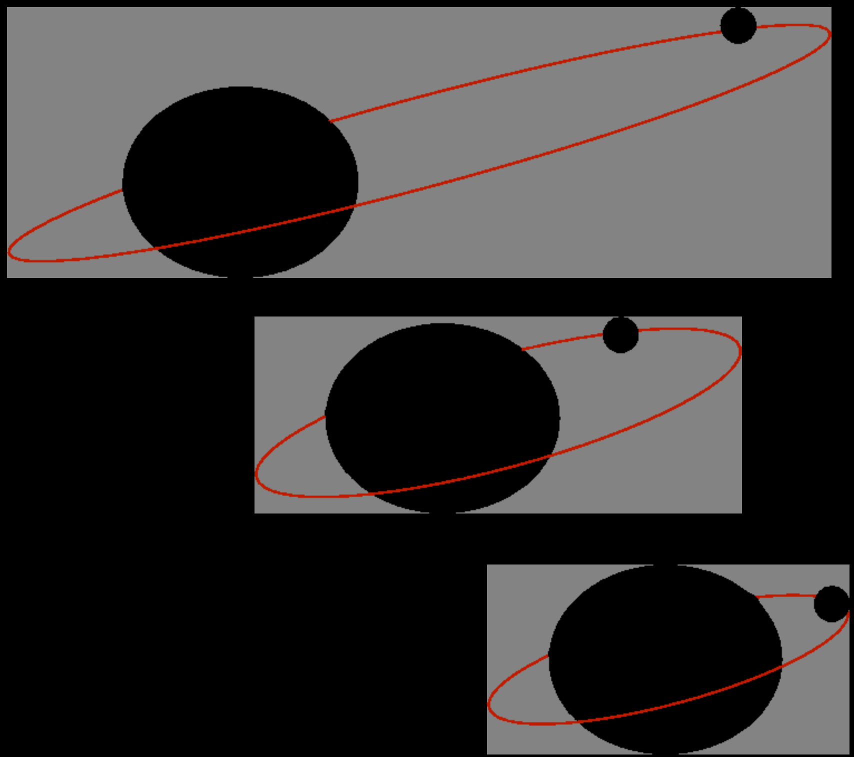
Means that EMRI events are predominantly stellar black hole captures!

EMRI events should be measureable to $z \sim 1$: Potentially *very* high event rate.

Really complicated chirping sources: EMRIs - Extreme mass ratio inspiral

Relativity view:

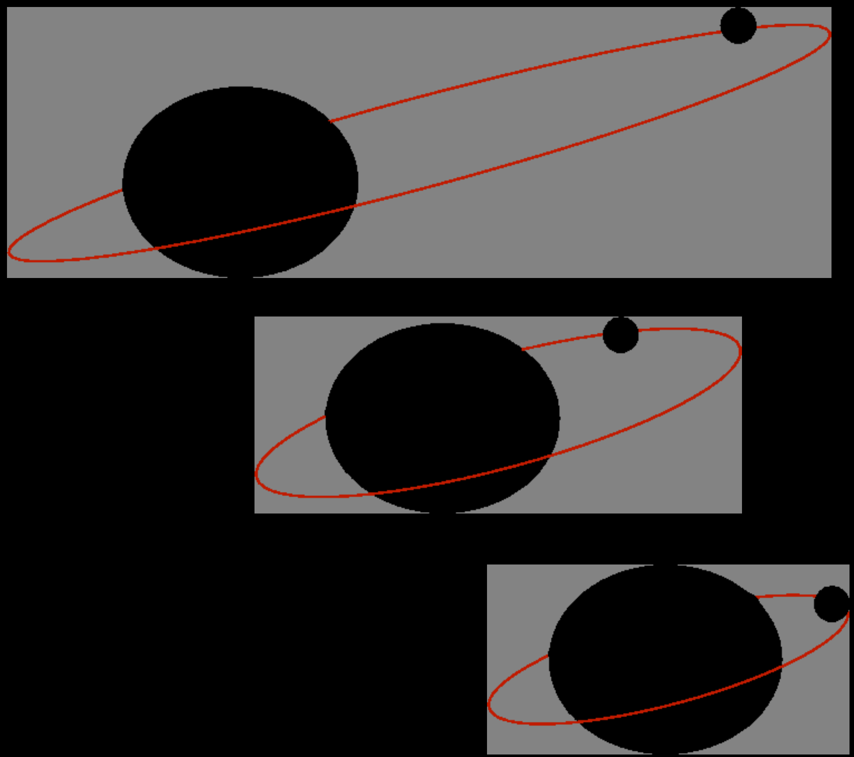
After scattering onto a strong field orbit of the nuclear black hole, smaller body spends ~1 year spiralling in due to GW losses.



Executes ~10^5 orbits as it spirals in.

Really complicated chirping sources: EMRIs - Extreme mass ratio inspiral

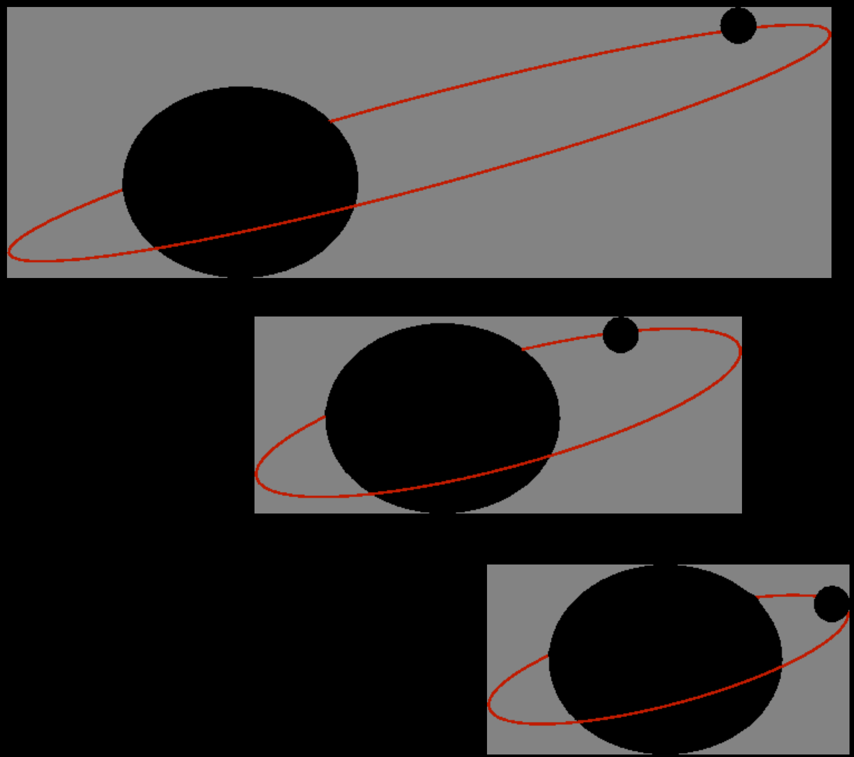
Track phase over those 10^5 orbits, can determine character of spacetime with high precision.



Prosaic application: Determine mass and spins of quiescent black holes with high precision.

Really complicated chirping sources: EMRIs - Extreme mass ratio inspiral

Track phase over those 10^5 orbits, can determine character of spacetime with high precision.



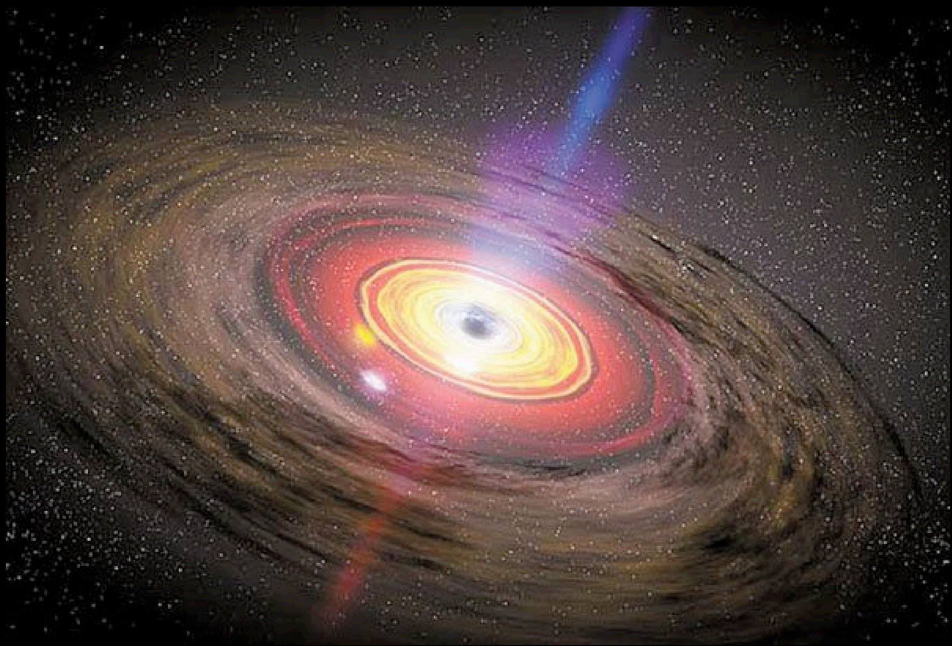
$$\delta M_{\rm BH}/M_{\rm BH} \lesssim 10^{-4}$$
$$\delta a \lesssim 10^{-4}$$

Barack and Cutler, PRD **69**, 082005 (2004).

Really complicated chirping sources: EMRIs - Extreme mass ratio inspiral

More fundamentally, test the character of the spacetime: Weigh its multipoles and make sure that they obey the constraints of the Kerr metric.

Tell the difference between this object:



Really complicated chirping sources: EMRIs - Extreme mass ratio inspiral

More fundamentally, test the character of the spacetime: Weigh its multipoles and make sure that they obey the constraints of the Kerr metric.

… and this one:

Summary: LISA source astrophysics

Weighing the dark and dense universe!

My biased opinion

Key input to astrophysics: Probing the growth of black holes. Circumstantial evidence of mergers is quite strong - a direct probe will open a window onto an aspect of structure growth that cannot be directly measured in any other way.